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# Structural Integrity of Wind Tunnel Wooden Fan Blades

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## Foreword

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## SUMMARY

This report presents information compiled by the NASA Inter-Center Committee on Structural Integrity of Wooden Fan Blades and is intended for use as a guide in design, fabrication, evaluation, and assurance of fan systems using wooden blades. A risk assessment approach for existing NASA wind tunnels with wooden fan blades is provided. Also, state-of-the-art information is provided for wooden fan blade design, drive system considerations, inspection and monitoring methods, and fan blade repair. Proposed research and development activities are discussed, and recommendations are provided which are aimed at future wooden fan blade design activities and safely maintaining existing NASA wind-tunnel fan blades. This report contains information that will be of value to wooden fan blade designers, fabricators, inspectors, and wind-tunnel operations personnel.

## INTRODUCTION

As a result of the catastrophic failure of the wooden fan blades in the NASA Langley Research Centers' 7- by 10-Ft High Speed Wind Tunnel on July 9, 1985, an inter-center committee was formed to study the potential implications for other NASA wind tunnels.

The charter of the committee was to develop methodology for evaluating and assuring the structural integrity of NASA wind-tunnel fan systems using wooden blades. Areas of investigation were to include design criteria/philosophy; fabrication criteria; analysis techniques; non-destructive examination methods and associated test equipment; frequency and type of in-service inspection and evaluation; repair methods; life evaluation; in-service monitoring instrumentation; and environmental effects.

This report documents the findings and recommendations of the Committee. The compilation of information on structural integrity of wooden fan blades is believed to be unique and without precedent with application to wind tunnel fan systems utilizing wooden blades.

## DESCRIPTION OF NASA WIND TUNNELS WITH WOODEN FAN BLADES

At present there are ten NASA wind tunnels with wooden fan blades. These are as follows:

### Ames Research Center (ARC)

1. 7- x 10-Foot Wind Tunnel No. 1
2. 7- x 10-Foot Wind Tunnel No. 2
3. 40- by 80-/80- by 120-Foot Wind Tunnel

### Langley Research Center (LaRC)

4. 20-Foot Vertical Spin Wind Tunnel
5. 12-Foot Low Speed Wind Tunnel
6. 14- x 22-Foot Subsonic Wind Tunnel
7. 30- x 60-Foot Wind Tunnel
8. 7- x 10-Foot High Speed Tunnel
9. 16-Foot Transonic Wind Tunnel

## 10. Icing Research Tunnel

A summary description of the blades' geometry, history, etc., for each of the NASA wind tunnels is provided in table I. With the exception of the Langley 16-Foot Transonic and High Speed 7- x 10-Ft Tunnels, none of the above facilities have replaced wooden fan blades because of wear, damage, or failure. The 40- by 80-/80- by 120-Ft Wind Tunnel blades were replaced during repowering. Current plans call for replacement of the wooden blades in the LeRC Icing Research Tunnel (IRT) in the near future. The IRT fan blades have been in use for 43 years, operating at speeds up to 460 rpm and temperatures as low as  $-20^{\circ}\text{F}$ . These blades were badly cracked but were repaired in 1986 and placed back in service under the cognizance of a NASA oversight committee made up of members from NASA Headquarters, LaRC, ARC, and LeRC. The reason for the longevity of these blades in the harsh environment is generally attributed to low operating stresses, particularly at the blade attachment.

The oldest blades still in service are located in the LaRC 30- by 60-Ft Tunnel. These blades are 48 years old and still appear to be in good shape. NASA's experience base indicates that lightly loaded wooden blades operating in a moderate temperature and humidity environment have excellent life.

A brief narrative on each of the wind tunnels is given in the following sections. More detailed information on each of these facilities (with the exception of the LaRC 12-Ft Low Speed Wind Tunnel) can be found in reference 1.

### Ames Research Center Wind Tunnels Using Wooden Blades

7- by 10-Ft Wind Tunnels.- The two NASA Ames Research Center 7- by 10-Ft wind tunnels are essentially identical as described in reference 1. The plan view of the tunnels is shown in figure 1. They are low speed ( $M \leq 0.33$ ), closed circuit, atmospheric wind tunnels. The temperature and moisture environment for the fans is generally quite good because the tunnels are usually operated at low speeds (and therefore low temperatures), and the environmental temperature and humidity at the site are generally favorable for wood. The mean value of relative humidity is 75% with an annual average at noontime of 62%; the mean annual ambient temperature is  $57^{\circ}\text{F}$ , and the daily average temperature varies from  $69^{\circ}\text{F}$  in August to  $47^{\circ}\text{F}$  in January. The fan inflow is not disturbed by upstream motor struts, turning vanes, etc. The fans were apparently designed for nonuniform but axially symmetrical inflow, but the gradient used was not correct. In the root area the blade angle used was too high, and some separation in the root area is thought to occur. In addition, the primary diffuser angle or area ratio is such that transitory separation occurs, and some unsteadiness or pulsing occurs. This in turn causes unsteady fan inflow which aggravates the root-area flow problem. The fan has never exhibited any structural problems (no cracking at all) because the stress levels are quite low (a few hundred psi). The fans have never had to be replaced. The fan blades are laminated Sitka Spruce and are covered with fiberglass and polyester resin; this has been sufficient to eliminate any foreign object damage.

40- by 80-/80- by 120-Ft Wind Tunnel.- The wind tunnel is a large subsonic, continuous flow, closed throat wind tunnel which was originally built in 1944. It was repowered and an 80- by 120-Ft test section was added as part of a nonreturn circuit which shared the repowered line. See figure 2 for a plan view of the tunnel. The

fans before and after repowering will be described and discussed, because they represent significantly different systems.

The original fans were fixed pitch laminated spruce. A single set of blades was used from the day the Facility was initially constructed (1944) until they were replaced during repowering (1981). For about the first 15 years of operation the blades were only covered with linen and doped. About once a year this covering system was replaced. The blades began to dry out and would occasionally suffer significant damage due to foreign objects. In August of 1960 the blades were covered with fiberglass. After this was done the covering system was maintenance free, and the foreign-object-damage problem was essentially eliminated. The only problem was the surface was not very smooth, and soot from jet or engine powered models would build up (after the soot built up the appearance was very similar to ice buildup on wings and was very sharp and jagged), and the performance would decrease. Because of the semirough fiberglass surface the soot was more difficult to remove.

The fan inflow was very poor because of the boundary layer buildup in the tunnel and because of the six fan arrangement. In addition the fans were less than a blade chord downstream of the motor support struts. The strut wakes caused a velocity defect such that stall would occur when the blades encountered the wakes. The resulting inflow was about as bad as could be encountered by a wind-tunnel fan. The fan was designed for axisymmetric and essentially uniform inflow. Despite the poor flow environment the blades did not exhibit any resulting structural damage, because the structural design was very conservative; that is, the stress levels were quite low (a few hundred psi). The most worrisome symptom was the noise character and level which was caused by the poor inflow (ref. 2).

During repowering, the drive was extensively changed (see refs. 2 and 3). One of the most significant differences was the fans were put well ahead of the motor supports. In addition the blading was designed to accommodate the poor inflow due to the boundary layer growth as much as reasonably possible. As described in reference 3 the result has been very successful. The most notable evidence is that despite absorbing nearly four times the power the noise of the new drive is significantly less.

The new fans are variable pitch, have a low maximum tip speed (377 fps) and are a wood composite. The highly loaded root area is made from a proprietary compressed Birch veneer material called Hydulignum\*; the major part of the blade is made from Sitka Spruce laminations, and the tip region is Balsa wood. The blades are covered with two layers of fiberglass with polyester resin which has been sanded very smooth to minimize the problem of cleaning off soot buildup. The temperature and humidity environment is essentially the same; that is, moderate. The air exchange rate was increased from about 2% to 10% to offset the heating caused by the increase in power.

The fan diameter remained the same at 40 ft, but the nacelle diameter was increased to 17-1/2 ft to accommodate the larger drive motors. A modified 65 series airfoil was used on a circular arc camber line. The solidity ranged from about 1.1 at the root to about 0.35 at the tip. There are 15 blades per fan.

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\*Trade name for densified wood manufactured by Permali, Gloucester, England.

In addition to repowering, a new nonreturn test leg with an 80- by 120-ft test section was added. During operation of this new circuit the fan environment and inflow are somewhat better.

During acceptance testing of the modified Facility the vane set upstream of the drive collapsed and destroyed the fans December 9, 1982; see reference 4. This necessitated replacing the fan blades as well as other repairs and modifications. Checkout testing and flow calibrations began September 1986 and research operations began in August 1988. The replacement blades required about 2 years for construction. If there had been no redesign or modifications required, the two years for the blade replacement would have determined the shutdown period.

#### Langley Research Center Tunnels Using Wooden Blades

The environmental temperature and humidity at the Langley Research Center is generally unfavorable for wood. The mean value of relative humidity is 72% with an annual average at noontime of 63%. The mean ambient temperature is 59.4°F and the average daily temperature varies from 79°F in July to 39.8°F in January. The combination of high humidity and high temperatures can result in significant excursions in moisture content and high operating temperatures in the fan region.

7- by 10-Ft High-Speed Wind Tunnel. - The LaRC 7- by 10-Ft High Speed Wind Tunnel is a high subsonic closed circuit, single return, continuous flow, closed throat atmospheric tunnel and is shown in plan view in figure 3. This tunnel has been operated since 1945 to support a wide range of subsonic tests and studies.

During operation at 0.8 Mach number on July 9, 1985, a catastrophic failure of all 18 Sitka spruce fan blades occurred. The failed blade set had been in use since 1975. In addition to blade loss, the main drive shaft was bent for a total estimated damage loss of \$1.7 million.

The findings of the investigation board (see references 5 and 6) attributed the failure to shear out at the root attachment caused by wood fatigue thereby leading to total destruction of the entire blade set. In addition, the flexibility of the drive shaft coupled with the small operating clearance between the blade tips and tunnel shell contributed to the rapid destruction of the blades and subsequent mechanical damage. Contributing factors were apparent inadequate design consideration of high stress concentrations at the blade attachment pin hole boundaries, fatigue, unsteady aerodynamic loading, and the thermal environment in the fan cavity. It was also found that the inspection techniques were inadequate, especially when assessing the criticality of detected flaws.

The dynamic loads due to blade passage through the wakes of the two upstream motor support struts were not accounted for in the design. This resulted in a 2 per/rev. type of loading. The assumed wake was verified by testing a 1/24 scale strut model and measuring velocity and pressure profiles in the wake.

A number of actions have been taken to minimize the risk of future blade failure. The replacement blades have been redesigned in the root/hub region to lower operating stresses; inspection procedures have improved and include periodic removal of blades; permanent drive vibration sensors have been installed; temperature measurement and monitoring in the fan cavity is being implemented, the blade/shell clearance has been increased; a foam witness pad has been installed to indicate changes in tip clearance, and frangible blade tips have been installed.

The interblade blade-root fairings have been completely redesigned. The new design is one piece and is molded construction made from a fiberglass/epoxy material and is bonded and bolted to the blade. Unfortunately problems were experienced with the fairing attachment in the initial shakedown operation and the fairings are now being redesigned. A massive interblade fairing failure was experienced in 1976 which was attributed to high operating temperatures in the fan region. The tunnel is red lined at 160°F in the fan region (see ref. 5), to minimize risk of reoccurrence,

20-Ft Vertical Spin Tunnel.- This tunnel was built in 1940 and upgraded in 1984 (see fig. 4). The spin tunnel is used to investigate spin characteristics of airplanes by testing free-spinning dynamically scaled models. The test section is vertical with 12 sides, 20 ft across the flats. The vertical test section is 25 ft long with a closed throat and annular return passage. Tunnel speed is variable from 0 to 90 ft/sec with acceleration to 15 ft/sec<sup>2</sup> and deceleration to 25 ft/sec<sup>2</sup>. Stagnation pressure is atmospheric; the turbulence factor is 2; and the Reynolds number per ft is 0 to  $0.62 \times 10^6$ . The test medium is air.

12-Ft Low Speed Wind Tunnel.- The Langley 12-Ft Low Speed Wind Tunnel is located in Building 644 and is shown in the plan view of figure 5. The tunnel was built in the late thirties and was called the NACA 12-Ft Free-Flight Wind Tunnel. The tunnel was originally used as a free-flight test facility but is now used for exploratory study of general aviation and military aircraft. Fundamental aerodynamic data with regard to lift and drag, including stability and control at high angles of attack, can be acquired at low speeds. Also, a monitor system permits flow visualization using tufts mounted on aircraft model wings. Photographic and video instrumentation permit the extraction of pertinent design data relative to a given model. Models to be tested may be mounted on one of several different static stings and/or on an oscillating sting. The 500 psi High Pressure Air Distribution System is utilized for prop driven models and other high pressure air requirements. The tunnel may be operated at air speeds from 0 to 90 feet per second.

The tunnel is constructed such that the circuit is an open-return type of octagonal cross section, 12 feet wide at the throat and 32 feet long. The housing of this tunnel is spherical. The tunnel is equipped with a DC motor and motor generator set to provide test air generation and velocity control to simulate flight conditions. For models requiring propeller simulation, the facility has a variable frequency set for propeller drive motors. For some models the facility also has a pneumatic system for model drive motor or modal engine simulation. The blades were fabricated from Sitka Spruce and the tunnel is operating with the original set of blades.

30- by 60-Ft Wind Tunnel.- The 30- by 60-Ft Wind Tunnel is a closed circuit, double return, continuous flow, open throat tunnel. Pertinent dimensions can be seen in figure 6. The facility is powered by two 4-bladed, 35.5 ft diameter fans, each driven by a 4000 h.p. electric motor. The tunnel operates at atmospheric stagnation pressure over a Mach number range of 0 to 0.14. The tunnel is used for large-scale aircraft, powered lift, helicopter, and free-flight dynamic model studies. The facility was constructed in 1930 and was upgraded in 1973 and 1984. The current set of fan blades were installed approximately 48 years ago and are in excellent shape. The blades were removed in 1987 for a detailed inspection which required removal of paint which had been used as a sealer. The environment generally tracks ambient conditions, i.e., is subject to swings in temperature and humidity of outside air. The excellent condition and long life is attributed to low operating stress even though the blades are subjected to dynamic loading as discussed in the next paragraph.

Because of the near proximity of the fans to the test section, inflow into the fans is very poor. Due to varying thicknesses of the boundary layer, ground board effects and model downwash effects the fan blades are subjected to dynamic loadings. As a result, significant vibrations of the motor support structure associated with the blade passage frequency (4 per rev.) have been troublesome over the years. Recently, aerovanes have been installed on the tunnel walls ahead of the fans in order to smooth the flow into the fans. As a result, the peak vibrations and hence the blade loading have been reduced by approximately 50%.

14- by 22-Ft Subsonic Tunnel.- The 14- by 22-Ft Subsonic Tunnel is a continuous flow, closed circuit, single return design. It operates at atmospheric stagnation pressure over a Mach number range from 0 to 0.28. The test section can be operated as either a closed or open throat design. A universal model support system uses a three-joint rotary sting mounted in a horizontal turntable with a  $\pm 165^\circ$  of rotation. The tunnel can be equipped with a moving-belt ground board with boundary-layer suction and variable speed for testing in a simulated ground effect. Models can be powered with either high-pressure air or variable frequency electric motors. This tunnel is used for force, moment, and pressure studies of full-span and semispan powered and unpowered advanced aircraft. The facility was built in 1969 and upgraded in 1984. A plan view of the facility is shown in figure 7.

The fan blades were installed in 1969 and are in very good condition. The inflow conditions are highly asymmetric and subjects the blades to n per rev. type loading. Because of the dynamic loading on the blades, strain measurements were taken to evaluate overall stress levels and remaining useful life. The measurements and data analysis revealed that dynamic stresses were of the same order of magnitude as the steady state stresses. Fortunately, the evaluation indicates that the measured stresses are well below the endurance limit fan for the laminated Sitka Spruce. The root stress is fairly high by comparison to other wooden fan blade systems and frequent inspection of the blade attachment region is warranted.

16-Foot Transonic Tunnel.- The 16-Foot Transonic Tunnel is a continuous flow, closed circuit, single return design as shown in figure 8. It operates at atmospheric stagnation pressure over a Mach number range from 0.2 to 1.3. It has a slotted throat octagonal test section and is equipped with dry high-pressure air for propulsion simulation using cold jets. Model mountings consist of sting, sting-strut, and fixed-strut arrangements. Model aerodynamic data measurements consist generally of force, moment, and surface pressures. Additionally the tunnel is equipped with a two component laser for flow-field measurements. The 16-Foot Tunnel is used extensively to support the Langley Aeronautics Program in propulsion integration for advanced aircraft including inlet and nozzle integration for fighter aircraft and pylon and nacelle integration for turbofan and turboprop transport aircraft. The facility was constructed in 1951 with two counter rotating fans located in the short leg of the tunnel. The fan blades were fabricated from laminated Sitka Spruce with a 6" thick by 3' wide butt. The blades are attached to the hubs with nine bolts (3 rows and 3 columns) and the aerodynamic surfaces covered with fiberglass and polyester resin. There are 26 blades on the front fan and 25 blades on the rear fan. The first set of blades developed significant cracks in the root transition region and were replaced after 30 hours service with a set of redesigned blades in this transition region. These blades were destroyed on February 1, 1951 by an interblade fairing failure and were replaced by an identical set April 15, 1951. Due to the harsh temperature (20°F-200°F) and humidity (0-100%) environment, these blades experienced cracks in the butt area around the attachment holes in the spanwise direction. These cracks were caused by dimensional change in the Sitka Spruce due to moisture migration and the inflexibility of the steel attachment pins and

plates. Therefore, the 1951 blades were removed in 1957 to fill all cracks with glue and to refurbish the tips. These blades were replaced in 1964 and again in 1976 due to extensive cracking. In 1986 the blades were temporarily repaired using Hydulignum face sheets to redirect the loads in the blade butt, while a new set of blades were being fabricated. These new blades have several design improvements. The butt portion will be fabricated from laminated Hydulignum sheets which is considerably stronger than wood, and the aerodynamic portion is fabricated from Sitka Spruce. Also the attachment holes have been elongated to permit dimensional changes with moisture.

#### Lewis Research Center Icing Research Tunnel

Icing Research Wind Tunnel (IRT).- The IRT is a specialized aerodynamics test facility in which research is conducted on the mechanisms of icing on aircraft wings and other structures, and in which devices for de-icing are tested for effectiveness. The IRT has been in operation since 1944, without replacement of major fan components. Recent rehabilitation of the tunnel includes the installation of a new, variable-speed drive motor. Typical operating parameters in the test section of the IRT are a wind speed of 300 miles per hour and a temperature of -20°F.

Figure 9 shows a schematic view of the tunnel and provides a reference for the locations and relative positions of key components. The IRT fan is mounted directly on the rotor shaft of the drive motor, in a position upwind of the motor and its supporting structures. As a result, fatigue loads that may be induced by distortion of the flow, due to strut blockage upwind, are not present.

The IRT contains refrigeration and water-spray equipment to produce ice on the test article. Because of the closed-cycle operation required to maintain tunnel temperature, fan blades are also subjected to icing and to impact from pieces of ice. Over the past four decades of operation, the wood fan blades have been found to be especially resistant to damage from ice. In addition, special procedures have been developed to monitor vibration in the drive, which would indicate excessive icing on the blades and unbalance of the fan in order to safely stop operations to de-ice the blades and prevent damage.

While there are similarities between the LeRC IRT fan blade and the LaRC 7- by 10-ft fan blade configurations, there are essential differences which a LeRC Review Committee (ref. 7) judged to be favorable toward the structural integrity of the IRT configuration. Two of the most significant differences are (1) much lower centrifugal loads at the fillet (blade root) cross section (44,000 pounds in the IRT blade compared with 171,000 pounds in the 7 x 10 blade) and (2) a redundant method of attachment at the hub (bolts plus clamping in the IRT hub, compared with bolts alone in the 7- by 10-ft hub). Reported operational experience at LeRC indicates that the clamping bolt preloads are increasing with run time, which suggests that the blades are swelling in the attachment regions.

#### HISTORY OF WOODEN BLADE FAILURES

##### Failure Modes

Very little information exists which documents wooden fan blade failures. The most recent documented blade failure occurred in the NASA Langley Research Center

(LaRC) 7- x 10-Ft High-Speed Wind Tunnel on July 9, 1985 (refs. 5 and 6). The findings of the investigation board attributed the failure to blade shear out at the root/hub region as a result of fatigue due to extremely high shear stress around the blade attachment holes. Another mishap of a similar nature occurred in recent years at the General Dynamics Convair Division, when a Sitka Spruce blade sheared out at the root at 800 RPM resulting in destruction of all the blades. This occurred on a 20-ft diameter, 6-blade fan. In both cases the failed blades were replaced with wooden blades which were redesigned in the root area. In general, other mishaps at NASA tunnels have been due to foreign objects impacting the blades, or other related type failures.

In 1979, a survey was conducted by Mr. S. B. Wallis of the Ford Motor Company in which he surveyed the membership of the Subsonic Aerodynamic Testing Association (see Appendix A) and provided information pertinent to spare blades, probability of accidental damage, affect of blade material on accident rate, and probable causes of accidents. It is of particular interest to note from Mr. Wallis' survey that of the nine reported accidents with wooden fan blades, six cases were attributed to design problems and four were failures at the blade/hub attachment which appear to correspond to the failure modes at the LaRC 7 x 10 and the General Dynamics Convair Wind Tunnels. Failures due to design problems were about double those due to foreign objects (or related).

#### Spare Blade Requirements

From the survey, it was found that of 14 major accidents, 4 were without spares at the time of the accident which resulted in down times ranging from 6 to 12 months. Of the 10 tunnels which had replacement spares down times of 0 to 4 months were noted. More recently in the case of the LaRC 7- by 10-Ft Wind Tunnel which did not have spares, the tunnel was down over 2 years. If spares had been available it is believed that this could have been reduced to 12 months or less which was the period required for other repairs and drive shaft replacement.

#### RISK ASSESSMENT AND PROBABILITY OF FAILURE DUE TO DESIGN PROBLEMS FOR EXISTING NASA WIND TUNNELS WITH WOODEN BLADES

An approach for assessing the probability of failure for NASA wooden fan blade systems was developed. Risk assessment classifications were chosen to be similar with those presently being used within NASA to evaluate facilities and are defined in figure 10. Numerical ranges assigned for frequent (high risk) are 4 to 5 to remote (1-2) for use in table II. Numerical weighting factors are assigned for the parameters shown in table II. A description of each follows.

Numerical weighting factors (scale of importance based on 100%) range from little or no influence on design life, e.g. 2%, to major factors relating to design life, e.g. 33%. For example, numerical weighting factors of 33 are assigned to stress and attachment shearout since these two design parameters are judged to be the most critical with respect to possible blade failure.

The probability of blade failure for the ten NASA wind tunnels with wooden fan blades can be estimated by using table II. The application of table II is a highly judgmental process. The criteria listed in table II are specifically for Sitka Spruce and/or Sitka Spruce/Hydulignum (or compreg) blades. The parameters listed in the first column can be readily obtained and are judged to have a measurable impact



on blade life. The first parameter is the peak stress at the blade root due to centrifugal force. The peak stress parameter is given a high weighting factor compared to the other parameters listed in the first column.

The criteria listed for temperature reflect the concern of operating at temperatures which exceed 150°F, or are below 20°F. There is a general consensus of opinion in the literature that wood suffers a permanent loss of strength at temperatures above 150°F. The lower limit of -20°F is based on a general concern of the committee for the LaRC IRT environment. Additional testing at these temperature extremes may reduce some of this concern in the future. The dynamic loads evaluation is a qualitative assessment of potential increase in blade stress and fatigue damage due to poor fan inflow (e.g., wakes from struts and asymmetric flow into the fan) or drive system dynamics that can induce blade loads. For example, the LaRC 14-by 22-Ft and 30-by 60-Ft Subsonic Tunnels are judged to have highly asymmetric flow into the fan. The moisture barrier sealant factor is based on the number of coats of resin and fiberglass covering the blade surfaces. Recent research at LaRC (see section on Environmental Effects) indicates that a coat of polyester or epoxy resin is very ineffective as a sealant, whereas four coats of polyester resin and two layers of fiberglass cloth is a good sealant combination. A fan blade operating in a dry environment (e.g., Ames) should not have a moisture problem with one coat of resin. However, a fan blade operating where there is high humidity before start up, and with a large (e.g. 100°F) change in temperature from start up to maximum operating conditions can experience severe cracking if not adequately protected. As an example, the LaRC 16-ft tunnel can experience large excursions in temperature and humidity, and the blades have a long history of cracking.

The attachment geometry is perhaps the most critical element of blade design. The types of attachments for the LaRC Wind Tunnel Fan blades are illustrated in figure 11. The blade configurations shown in figure 11 are drawn to the same scale for relative comparison purposes. This design dates back to the early forties when most of the wooden fan blade systems were designed.

The attachment shearout addresses the bolt or pin hole pattern in the blade butt. A significant risk exists when a line drawn from the outside diameter (OD) at one hole to the OD of the hole below it makes an angle  $\theta$  less than 10° with the wood grain (see fig. 12). This type of attachment pattern is a high risk if the shearing along these lines could lead to the single mode shearout of a plug of wood as illustrated in figure 12. Also, edge distance (distance from loaded bolt hole(s) to free edge) can lead to stress risers with high potential for crack growth away from the hole and into the hole if the distances become too small. A distance of several diameters is highly desirable.

The airfoil to root transition is based on a concern with the contour changes between the normally rectangular blade butt and the aerodynamic blade profile. If this transition consists of a gradual decrease in area from the blade butt to the blade profile, then the risk is low. However, if the transition occurs in a short length with the smallest cross-sectional area occurring between the blade butt and the blade profile, the risk is high. (Figure 13 shows the finite element model of the 7- by 10-Ft Wind Tunnel blades to butt transition which illustrated the short transition length and the redesigned transition.) This assessment is based on detail stress analyses performed at LaRC which indicate that for orthotropic wood properties the radial loads that exist at the smallest area do not uniformly spread out in the larger cross section area in the blade butt. Instead, these loads tend to remain concentrated in a small core region in the butt about the same as the smallest root area.

Concentration of the loads over a small area can result in high localized shear stresses in the blade to hub attachment region. The combination of attachment shear-out geometry, short transition, and high localized shear stress resulted in shearout of the LaRC 7- by 10-Ft Wind Tunnel blades. Historically (see Appendix A) this has been the major cause of wooden blade failures.

The length of service factor is based on accumulated experience at LaRC over the last 40 years. Length of service is a highly qualitative parameter since it is a measure of wear-out which covers such factors as lack of maintenance, long time exposure to environment, deterioration of the wood, etc.

The visual appearance of blades is also a qualitative assessment factor. A "poor" rating would be assigned to a blade which had cracks through the entire blade butt depth and which run from one hole to the next or to an outside surface. Conversely, a "good" rating implies there are no through the butt cracks, but only surface cracks due to such causes as moisture migration.

The probability estimate of failure is obtained by using the following equation:

$$\text{Probability of Failure} = \frac{\sum (\text{Weighting factor } \%)_i \times (\text{Risk Assessment Factor})_i}{100}$$

i = ith parameter

Table II-A illustrates the table completed by committee members and LaRC engineering personnel. Since the assignment of failure probability and weighting factor is judgmental it is suggested that the user of these tables assign values based on their personal knowledge of the facility. The resultant number will range from 1 to 5. For example, the sample calculation for the current LaRC High Speed 7- by 10-Ft blades given in table II-A is 3.7 (occasional). The same assessment applied to the old blade design for the LaRC 7- by 10-Ft would have put it in the frequent (high risk) category with a probability factor of 4.7.

Fan blade systems that receive a 4-5 probability estimate should be replaced. Blades receiving a 3 to 4 level assessment should be removed and closely inspected for other factors (e.g., through cracks in the butts) that may not readily be apparent. Also a more detailed load and stress analysis or restricted operation may be in order for any of these levels.

## STATE OF THE ART FOR WOODEN FAN BLADE DESIGN

### Materials Data Base

Sitka Spruce has traditionally been a choice material for wooden fan blade systems within NASA. However, recently a new densified birch veneer material has been used (1) in the blade butts of the Ames 40- by 80- by 120-Ft Wind Tunnel; (2) as a facesheet for the repair of the LaRC 16-Foot Transonic Tunnel blades; and (3) for the butt section of the new LaRC 16-Foot Transonic Tunnel blades. The particular material used is proprietary, called Hydulignum, consists of compressed birch veneers, and is similar to compreg of reference 8. This shift to a densified wood in the butt region is to satisfy the need for higher strength (bearing and cross grain strength) in the attachment region for several of NASA's tunnels. The mechanical properties of

the densified wood can be tailored to the design requirements by the selection of laminate orientations and densities.

The strength properties for the Sitka Spruce at room temperature are readily available in the literature, for example, see the Wood Handbook (ref. 8). The values used for NASA Langley's analysis are listed in the first row of table III. These values have been adjusted from data published for 19% moisture content (m.c.) to 8% moisture content, because measurements of moisture content in LaRC's existing wood fan blades indicated that 8% is a typical value. The allowable stresses for Sitka Spruce are discussed in the next section.

Also listed in table III are strength values at room temperature and 200°F for Hydulignum. These values were obtained from the manufacturer, and were established to be 10% less than the minimum test values in order to be conservative. The strength values for Hydulignum at 200°F were determined by test and the values given are at least 10% less than the minimum test values.

There are no readily available, published data for Sitka Spruce at elevated or extremely cold temperatures; therefore, the procedure discussed in the next section was used to estimate the decrease in strength with temperature. Some elevated temperature shear strength and fatigue data for Sitka Spruce were developed at LaRC and are shown in figures 14 and 15. Also the material constants for both Sitka Spruce and densified wood are listed in figure 16 as used in LaRC's orthotropic analyses of its wooden fan blades.

The "Wood Handbook" and other available publications (see refs. 9 and 10) provide a large data base for wood mechanical properties and accounts for moisture and temperature effects to a large extent. Recent testing of Sitka Spruce on material obtained from the LaRC 7- by 10- and 16-Ft fan blades basically confirmed existing strength and fatigue data found in the literature.

A recent publication (ref.~11) presents a compilation of static and fatigue strength data for laminated wood material made from Douglas Fir and Epoxy. Also, results of test data provide insight into the effects of variables such as moisture, size, lamina-to-lamina joint design and ratio of cyclic stress to steady stress during fatigue testing. The data provided in reference~11 were obtained during development of wood rotor blades for large scale wind turbines.

### Failure Theories

Failure theories which were developed for orthotropic lamina for biaxial loading conditions are given in reference 12. These theories are judged appropriate for application to laminated wood structures. In particular, the tensor polynomial theory (Tsai-Wu) has been evaluated by Liu (ref. 13) and recommended for use in predicting the strength of wood under combined stress states.

In engineering practice there are many implications that must be considered when selecting a failure theory. Situations involving large deflections, buckling, impact, and fatigue require design considerations in addition to the failure theories described in the references. In particular, stress risers are of significance with respect to the issue of fatigue design of wooden blades which is discussed in a subsequent section. The failure theories given in reference 11 account for biaxial loading in strength design.

## Allowable Stress

The allowable stresses for Sitka Spruce were determined using procedures outlined in references 14, 15, and 16. The clear wood average strength was obtained from table II of ASTM D 2555 and are shown as the top number in the first column of table IV. This table was developed specifically for application to the LaRC 16-ft fan blade analysis. Rather than using a factor of safety, the AITC uses the 1% strength value plus several adjustment factors that account for moisture content, specific gravity, strength ratio, load duration, manufacturing process, stress concentration, end position l/d ratio, and temperature. The 1% strength value is that value at which 99% of all test data will fall above, and it is shown as the second number in column one. Listed in table IV are the adjustment factors and the resulting stresses. The adjustment factor for the 1% strength was obtained from reference 13. The adjustment factors to go from clear wood (19% m.c.) to dry wood (12% m.c.) were obtained from table A1, ASTM D 2555, and the factors to go from 12% m.c. to 8% m.c. were obtained from reference 14. Note that the first stress value in this third column corresponds to the strength values given in table III. The strength ratio factor was obtained from reference 15 and it accounts for the effect of knot size, grain deviation and general slope, end splits, and seasoning checks and shakes. The load duration is based on 2500 operating cycles in 10 years and it was obtained from reference 14. The adjustment factors for columns 7-10 were obtained from table 9 in reference 15. The temperature adjustment factor was based on a 1/2% strength reduction for every °F above 70°F. This relationship is discussed in references 16 and 17.

The properties of Hydulignum are not as well documented as for wood; therefore the procedures for determining the allowable stresses are not as well established. The mechanical property data for Hydulignum for multiple test specimens do not have large deviations like that for wood.

Examination of the allowable stress of table V compared to the published strength values is indicative of the large safety factors used in the literature to account for the many variables.

## Safe-Life Design (Fatigue and Fracture)

Consideration of fatigue in the design of wooden structures is usually considered to be secondary. Fatigue tests have shown that the endurance limit for wood is generally around 40% of its static strength. In cases where the working stress levels are less than 40% of the wood strength (see fig. 15), fatigue is usually not a problem for most wood structures. However, local stresses if not properly accounted for in the wood near bolt or pin attach holes can exceed endurance limit stresses. For room temperature, the fatigue curves given in reference 8 can be used.

Work performed at LaRC to study the 7- by 10-Ft High Speed Wind Tunnel fan blade failure identified fatigue failure associated with high shear stress around the pin holes. Also, since the cyclic loading on fan blades may be complex and generally does not occur at stress ratios ( $S_{min}/S_{max}$ ) of zero, fatigue data should be adjusted for mean stress effects. Limited tests at LaRC suggest that the modified Goodman diagram can be used to approximate the effect of mean stress for wood. Although the Goodman approach is valid for metallic materials, it remains questionable whether it is valid for wood (composites). Further work is needed in this area. Based on the history of wooden fan blade failures and the complexity of stress distribution in

blade to hub attachments, the committee feels that there should be future fatigue testing which is focused on pin loaded holes.

Application of fatigue data. - The consequences of operating with high stress for the 7- by 10-Ft blade were evaluated by performing a classical fatigue analysis using a S-N curve and modified Goodman diagram. A modified Goodman diagram for laminated Sitka Spruce loaded in shear is shown in figure 17.

The basis for a fatigue evaluation is to establish a load-cycle history based upon the best estimate of actual facility operational history. Of particular importance is the operation at high loading conditions. The cyclic stress associated with the LaRC 7- by 10-Ft Wind Tunnel high speed (high loading) operation is illustrated in figure 18. When assessing the number of cycles due to the effect of dynamic loading, the minimum stress value is taken from the steady state loading, while the dynamic contribution is obtained from the steady-state plus dynamic loading. In the case of the 7- by 10-Ft blade the dynamic loading (2 per/rev.) is associated with blade inflow disturbances from the two motor/nacelle support struts (see ref. 18). The stress cycle should be chosen to give the largest alternating component, and hence, the largest mean stress.

Since most S-N curves will be developed for a single R value (minimum-stress/maximum-stress), the data may not be directly applicable to the stress cycles being analyzed. As previously stated, this difficulty may be accounted for by constructing a modified Goodman diagram. This diagram is constructed by plotting the fatigue strength (alternating stress component for a given number of cycles) on the R ratio ray, from the given S-N curve, and projecting from these points to the ultimate strength (maximum mean stress with zero alternating component). By doing this for each value of cycles to failure (N), then constant life curves may be constructed as shown on figure 19. Figure 19 illustrates the fatigue life predictions for the old and new design of the 7- by 10-Ft blades. This figure shows the points on the diagram relating to operational and 2 per/rev. cycles. As can be seen on the diagram the redesign resulted in an improvement in predicted life of almost two orders of magnitude.

There are numerous theories for predicting design life that involve the gradual accumulation of damage during operation. Generally, Miner's rule (a linear damage theory) is used. This method expresses, in terms of cycle ratios ( $n_i/N_i$ ), the effect of fatigue damage cycles ( $n_i$ ) at a stress level to the total operational damage cycles ( $N_i$ ) at the same stress level. Failure is then defined to occur when the sum of all of these ratios equals unity, i.e., 
$$\sum_{i=1}^u \frac{n_i}{N_i} = 1.$$

A high variability in fatigue properties coupled with variability in actual stresses, and cyclic life sensitivity to small variations in stress when operating at a high mean stress value will preclude accurate prediction of failure. The fatigue evaluation should suggest when conditions are present such that the peak stress excursion associated with operation cycles may contribute to fatigue damage (i.e., crack initiation and growth). From a design point of view, the alternating and mean components for the appropriate stress ratios should fall below the infinite life line (endurance limit). The validity of the classical fatigue assessment may raise questions due to the large variation in fatigue properties, application of laboratory fatigue data to the actual structure (which will have a complicated stress pattern), assumption of linear damage, etc. However, the methodology outlined can be used as a

tool to assess fatigue damage safety margins. A safety factor at least 4 (including stress concentrations) on peak stress is highly recommended for fatigue design.

Fracture mechanics applied to wooden structures.- Considerable work has been done at Forest Products Laboratory on applying Fracture Mechanics to wood (see refs. 19 through 21). However the technology has not been developed to the point that it can be used for fatigue design or evaluate remaining life given a crack size and stress distribution.

#### Environmental Effects and Experience at NASA Centers

The effects of moisture and operating temperatures have to be considered in both the design and maintenance of wooden fan blades. Generally speaking, environmental effects of temperature and humidity on strength properties have been studied and data are available in the literature. Of particular concern should be large excursions say in temperature above 150°F or below 20°F during operation. For example, prolonged exposure above 150°F can result in a permanent loss in strength (see fig. 13). For this reason it is important that operating temperatures in the fan region be kept to a minimum. Fan cavity heating (see ref. 22) is of particular importance since cavity temperatures (depending on exchange of air with the free stream) may be much larger than free stream temperature.

The combination of larger temperature and moisture excursions have to be accounted for in both design and evaluating remaining blade life. Good examples are the LaRC 16-Ft Transonic Wind Tunnel and the LeRC Icing Research Tunnel. The 16-ft transonic tunnel operating temperatures range as high as 200°F and 100% humidity. By contrast the LeRC IRT blades see temperatures as low as -20°F and ice forms on the blades during operation. It is believed that the severe environment in the IRT contributed largely to the initial cracking observed in the blades.

Ames Research Center.- Environment has not been a major problem but it has tended to dry out the fan blades. This has only been a problem if there is foreign object damage because the wood tends to become more brittle. Blades used at Ames are sealed and protected with two layers of fiberglass and polyester resin; this has been adequate protection.

Langley Research Center.- Moisture content of blades at LaRC is affected by weather conditions as well as operating conditions. As previously mentioned, extreme temperatures are encountered in tunnels such as the 16-Ft Transonic Wind Tunnel and 7- by 10-Ft High Speed Wind Tunnel. Red line temperatures are established for the fan regions but not necessarily because of the wooden blades. For example, for the 7- by 10-Ft Wind Tunnel which experienced wind tunnel blade failure, the red line temperature was established to protect the interblade fairings. Generally, the LaRC tunnels tend to go from high humidity conditions to dry conditions during operation and back to relatively high humidity conditions. Moisture and temperature effects are believed to be a major factor in cracking of the 16-Ft Transonic Wind Tunnel blades.

Lewis Research Center.- As previously stated the IRT blades are subjected to water, ice, and extremely cold temperatures. Even so, the blades have been in operation since 1942. Severe cracking has occurred in the blade to hub transition region, primarily in the glue joints. Indications are that most of the cracking occurred soon after initial installation. The blades were refurbished, cracks were filled and installed in 1986. These blades are due to be replaced in 1990 or 1992.

Design recommendations.- Sealing of the blades is extremely important. Numerous fiberglass and resin combinations have been investigated at LaRC to determine the most cost effective sealing system. Results of this study are summarized in figure 20 where moisture exclusion efficiency versus time is shown for the sealing systems investigated. The moisture exclusion efficiency is defined as the difference between the amount of moisture gained by an uncoated specimen to the moisture gained by coated specimen, normalized by the moisture gain of the uncoated specimen. The numbers in front of the symbols indicate the number of resin coats or the layers of glass used for that particular coating system. This work suggests that four coats of polyester resin with two layers of fiberglass cloth provide an excellent moisture barrier. Another approach is to cover the blades with plastic. This approach has been used for aircraft wooden propellers in severe weather environment (see ref. 24).

## Design Loads

Overview.- Potentially there are many load cases that can affect the fan design. To ensure a good design all relevant load cases should be considered. The load cases and their relative importance depend on details of the fan and drive system configuration and operation, and on details of the wind tunnel configuration and operation. The load cases described are those which should be evaluated for importance, because they have actually been encountered over the years and have been found to be important for various wind tunnels.

Design approach.- Aerodynamic and centrifugal loads essentially govern the blade design. Generally, blades are raked and swept in order to null out aerodynamic bending loads (generally at max. rpm). The procedure for doing this is well known and should be used. Of particular importance is how these loads are transmitted into the hub region. Care should be taken in the design to distribute the loadings into the hub attachment area as uniformly as possible. Historically, this is where most blades have failed.

Loads cases.- It is important to include all loading conditions that may be encountered. There are a variety of different conditions which create different fan loadings. Discussion of those which may be encountered follows. The load cases are summarized in table VI.

Transient loads.- Starting; normal controlled acceleration and deceleration; emergency stops, dynamic braking, mechanical braking, aerobraking, etc.; pulses due to the drive motors, especially during starting. Acceleration and deceleration due to changing motor input power characteristics such as transferring from variable frequency power to constant frequency power. Solid-state power systems can cause pulsing of the drive system and dynamic loads on the fan.

(a) Wakes from models and their supports can cause a strong once per revolution disturbance. Unpublished data indicate this can be very large. It can be either a direct wake effect or an indirect wake effect which causes a diffuser problem which in turn can cause poor fan inflow. For example, if ground effect testing is done with the model close to the floor this can cause poor flow on the floor of the primary diffuser and cause separation. This in turn can cause a major velocity defect for the flow into the fan near the floor.

(b) Boundary layer effects which can be a once per revolution, or higher frequency disturbance. This was a major design problem for the 40- by 80- by 120-Ft Wind Tunnel because of the multiple drive units; see reference 3.

(c) If diffusers are improperly designed (wall angle too high) the inflow to the fan can be distorted as well as unsteady. Often the diffuser is designed for optimum performance with minimal consideration of model or model support effects on diffuser performance. Large models and their supports can adversely affect the diffuser and nonsymmetric fan inflow can result. Typically a strong once per revolution disturbance results.

(d) If they are improperly designed, turning vanes can cause either over or under turning of the flow. This can cause a strong once per revolution disturbance.

(e) Some wind tunnels have external drive motors and have a drive shaft in the airstream which results in a wake and therefore disturbance to the fan inflow. This can cause a disturbance that occurs once per revolution.

(f) The fan contraction can cause an undesirable loading. A traditional problem is that caused by a contraction which is also a transition from square or rectangular to round; this can cause a disturbance which occurs four times per revolution.

(g) Fan nose cones and their supports can cause disturbances to the fan inflow. There is usually a relatively small velocity defect at the blade root due to the nose cone boundary layer buildup which is usually not a big problem. An often more significant problem is that due to wakes from the nose cone supports. To prevent this some care should be exercised with their design (nonradial, well forward, low thickness, etc.) to minimize the effects of the wakes.

(h) The effects of inlet guide vanes (or upstream stators if there is more than one stage) can be minimized in traditional ways as is done for typical compressors. Care should be used when selecting the number of vanes, and the spacing should be at least two vane chords, if possible.

(i) Exit guide vanes or stators can sometimes cause a problem for fan blades because of their potential flow effects. If they are close to the fan they can cause significant fan inflow angularity distortions. This problem can be made insignificant by using a spacing of a couple of blade chords.

(j) Drive supports are always large and can cause fan loading problems. If the fan is downstream of the supports the wakes from the supports can cause large velocity defects and significant loading problems for the fan. The wake effect can be minimized by careful shaping of the supports, using as large a clearance as reasonable, and making the supports nonradial so the wakes do not line up with the blades. If the fan is upstream of the supports, the flow around the supports ("potential-flow" problem) can cause undesirable flow effects forward at the fan. This problem is much easier to deal with than that due to the wake, because it generally involves a flow angularity variation rather than a velocity defect effect. The approaches to take to minimize this problem are the same as for minimization of the wake effect.

(k) For wind tunnels which use variable pitch fans or variable camber inlet guide vanes for control, the blade loading distribution will be nonoptimum except at the design condition. There can be very large variations in blade loading distributions over the airspeed range of the wind tunnel.

Lift amplifications.- Dynamic blade lift amplifications can be encountered similar to that for helicopters if the inflow velocity varies around the azimuth. Even if stall does not occur and the blades are very stiff, dynamic loading can cause a maximum load which is higher than the predicted maximum static load. If stall is



encountered and then recovery occurs as the blade goes around the azimuth a very large amplification in loading can occur. See reference 23.

Unknown inflow.- If the inflow distribution is unknown, a reasonably conservative assumption is to assume the inflow ahead of the contraction is the same as for established turbulent pipe flow. In addition, conservative unsteady load should be assumed. A once per revolution load that is at least  $\pm 25\%$  of the steady load should be used.

Instrumentating for loads.- In many cases dynamic loads cannot be determined with any great accuracy and usually must be estimated. Where possible, particularly for a new blade installation, the blades should be strain gaged to obtain both steady-state and dynamic stresses at critical locations.

### Ease of Maintenance and Inspection

Proper maintenance and inspection are critical to assuring continuing safe operation. Information is presented elsewhere in this report which pertains to maintenance and nondestructive examination methods and/or procedures. The following recommendations are provided for design of new systems. Cost considerations may preclude incorporation of all of these recommendations but each should be carefully evaluated.

1. Design the fan system to be readily removable. For large fans it may not be economical to accommodate convenient fan removal; however, lift points should be included in the structure over the fan. As a minimum, the fan should be designed so individual blades can be readily removed.

2. The fan should be designed for convenience of repair and inspection including the following:

- (a) Readily replaceable tips. This is the area most frequently damaged.

- (b) Use a clear finish on the blades to improve the ability to inspect for delaminations and cracks.

- (c) Include a mechanism which allows the drive shaft to be easily rotated for inspection. If the drive uses bearings with lift pumps, there should be a convenient control so the lift pumps can be turned on to allow the drive shaft to be easily rotated.

- (d) Obtain appropriate blade handling fixtures and make sure there are blade lift points which are clearly marked. Lift devices, access stands, access hatches, etc., should be included.

### Frangible Tips and Tip Clearance

Frangible tips.- Frangible tips are very desirable, since they can minimize damage to blades if foreign objects gets jammed under the tips. LaRC experience indicates a high level of blade damage due to foreign objects is possible without frangible tips. It is suggested that the tips have a radial length of at least 2 inches.

Blades redesigned for the LaRC (High Speed 7- by 10-Ft and 16-Ft Transonic Wind Tunnel) utilize frangible tips. At Ames the new 40- by 80-/80- by 120-Ft Wind Tunnel

blades have frangible tips whereas the old 40- by 80-Ft Wind Tunnel blades and the ARC 7- by 10-Ft Wind Tunnels do not. The Icing Research Wind (IRT) Tunnel has tips which break off readily so that blade damage is effectively eliminated. The tips can be readily replaced. At IRT the parting lines are angled so that wedging action which would tend to cause more extensive blade damage is eliminated. This appears to be an excellent design approach to the problem.

Tip clearance.- Sufficient tip clearance is required to allow for blade growth, shroud movement, and drive shaft displacement. Excessive clearance can reduce performance. References 24 and 25 recommend that for every 1% increase in tip clearance divided by blade height the efficiency will be reduced 2%; however, reference 24 warns that for blades with aspect ratios  $>2$  (as many wind tunnel fans are) the reduction may be even larger. It is important to make the shroud as round as possible to minimize variations in loading and to minimize the tip clearance required. An achievable tip clearance and variation for a 40 ft diameter fan is  $1\frac{1}{2}$  inches  $\pm$   $\frac{1}{2}$  inch. Smaller values are extremely difficult or costly to achieve. Relaxation (say double) of this tolerance would save a small amount in fabrication cost. It is important to center the fan in the shroud as well as possible. The drive system should be designed so some adjustment is possible during installation; shims, jacking bolts, etc., should be used.

Provisions should be made for measuring tip clearance during operation and to measure the static clearance on a periodic basis. One approach is to bond a foam witness pad to the tunnel wall that is thick enough to touch the longest blade at the point of minimum clearance. By coating the pad with a witness paint after wear in, any change in blade growth will be indicated by scraping of the coating. Any indication of blade growth should be followed up with a detailed inspection. Recently a technique was developed at LaRC to measure fan blade tip to shroud clearances using magnets and Hall-effect transducers. The method requires mounting a permanent magnet in the end of the fan blade and monitoring the tip to shroud distance by use of Hall-effect transducers affixed to the surface of the shroud. (See ref. 26.) The technique has been successfully demonstrated on a laboratory prototype.

#### Foreign Object Damage/Protection

In conjunction with the use of frangible tips which was discussed in the previous section leading edge protection is required for protection from occasional foreign objects. Fiberglass and/or celastic have been found to be very effective. Probably the most developed leading edge protection is that used at the Lewis Research Center Icing Research Wind Tunnel. A hardwood (maple) is used at the leading edge (approximately a  $\frac{1}{2}$  round section) to help improve the impact resistance. The entire leading edge area is covered with a rubber like material that is used for de-icing boots. This system has evolved because of the necessity for protection from chunks of ice shed from models and wind tunnel components.

#### Proof/Component Testing

Proof testing.- For a new fan design, as much testing as practical is desirable. Generally the root area is the critical structural area and testing should be focused on this region. Root pull and fatigue tests are very desirable and are mandatory if the design stress level is very high ( $>1,000$  psi for Sitka Spruce) or if a new hub attachment concept is being used. Full scale or prototype tests are

required; however, scale model tests may be helpful during design development. Eventually full scale static and dynamic testing may be required. Generally a conservative rule of thumb for static testing is that if a stress level of 3 times design is achieved with no signs of failure (including local cracking and delamination) the design is acceptable.

Proper loading of test specimens is often a problem. It is difficult to simulate the loading and the strain distributions the blade will actually encounter. The approach that was used for the repowered 40- by 80-Ft Wind Tunnel was to build full size, special double ended specimens that allowed the proper root loading. The specimen was designed so that the loading and strain distributions near the root would be matched. This was done for static pull tests.

During proof testing useful data can be obtained from surface mounted strain gages. Strain distributions can help verify analytical modeling of the blade. Location and magnitude of surface stress concentrations can be verified.

Special full-scale fatigue specimens were also fabricated for the repowered 40- by 80-Ft Wind Tunnel. Only the critically loaded root section and adapter were modeled. Beyond the area to be modeled a constant section was fabricated and then shaped for the fatigue test fixture.

Coupon testing.- There is a variety of kinds of coupon testing, and it is important to have a comprehensive test program. Types of testing are described in many of the references given in reference 6. As a minimum, wood properties and glue joint properties need to be verified to ensure adequate wood and glue joint quality during construction. Material properties for a given kind of wood can vary substantially, and it is important to verify the properties used for design. Gluing procedures must be carefully done and require good quality control, and regular testing is mandatory to ensure maintenance of adequate quality during fabrication.

Verification testing.- After the fan has been constructed and installed, strain gage tests are highly desirable to verify the design and loading conditions. If strain levels are beyond acceptable levels, consideration should be given to derating the drive or to implement more comprehensive monitoring and inspection systems.

Spin testing.- Spin testing of a prototype blade is highly desirable. Since the aerodynamic loading on the blade is not represented in a spin test, the chief value of such a test is to verify the design of the blade transition and root attachment area. The test can also serve to test the fairings in the centrifugal force field in cases where the fairings are attached to the blades. A recent example of a spin test for a NASA wind tunnel blade design was the National Transonic Facility fan blade spin test carried out in the Wright-Patterson (AFWAL) spin facility. Generally speaking these facilities for doing spin tests are limited, and in virtually all cases special fixturing will be required.

#### Hub Attachment

In addition to the attachment methods shown in figure 11, there are a variety of other hub designs and blade attachment methods. Generally, it has been found that for low blade loading (low stress) in the attachment region, no problems were encountered. However, failure experience indicates that for highly stressed blades, shear out or pull out of blades at the hub attachment has been the predominate failure mode. One of the chief factors appears to be the load distributions in the

attachment bolts/pins which are dependent to a large extent on the transition from the aerodynamic part of the blade to the hub area. The LaRC 7- by 10-Ft High Speed Wind Tunnel design is a good example, where due to the very sharp transition, the centrifugal loads were distributed over about 1/3 to 1/2 the length of the attachment pins resulting in high localized shear stresses, leading to fatigue failure. Whereas, earlier blades (different airfoil shape) used in this tunnel had thick transition sections (attached to the same hub) which resulted in a much better distribution of the loads. Also, it is apparent that for many of the earlier designs, handbook analyses were not sufficient for predicting high localized stresses, nor was fatigue a consideration in the design. Generally, simplifying assumptions were made and low allowable stresses were used which were supposed to account for uncertainties and usually worked reasonably well.

Where possible, state-of-the-art analysis tools (see ref. 27) should be used to perform stress analyses in the hub attachment region. This allows for a more optimized design and for use of higher allowable stresses. See reference 27 for further insight to high stress problems which may be encountered. The repowered ARC 40- by 80-Ft Wind Tunnel uses a hub which allows variable pitch. The root area of the blade is made of a compressed wood material (Hydulignum which is similar to Compreg in ref. 10) which is threaded (tapered section) into a metal adapter. The metal adapter has a flange which is bolted to pitch-shaft flanges on the hub which produces the pitch motion of the blades. The root area of the blade is well sealed to prevent moisture and temperature cycling from causing the threaded root sections to loosen. Full scale pull and fatigue tests were performed on this system in addition to a finite element analysis.

#### Analytical Techniques for Stress Prediction

In the past, simple hand calculations were performed to determine several critical stresses in a fan blade. The average tensile stress was determined using the centrifugal force and the minimum cross-sectional area of the blade. The maximum shear stress was determined using the minimum shear out area in the bolt region of the blade butts. Both of the stresses were nominal stresses and did not represent the true peak stresses in the blade. With today's finite element programs, a very detailed stress distribution can be estimated. Both the 7- by 10- and 16-Ft High Speed Wind Tunnel fan blades at LaRC were analyzed with finite element models. These models included details of the blade geometry, orthotropic properties of the wood, and were sufficient to determine the stress distributions around each of the bolt holes in the blade butts. A description of the analytical results for the 7- by 10-Ft High Speed Wind Tunnel is presented in reference 26. Aerodynamic loadings, centrifugal forces, moisture changes, and thermal stresses were simulated in these models. Several interesting results were obtained from these models. For both tunnels the bolt or pin loads varied significantly as shown in figures 21 and 22. In addition for the 7-by 10-Ft Wind Tunnel blade butt, the stress contours below the minimum area did not expand back out to the full thickness of the blade butt. This effect further concentrated the nonuniform bolt loading. For the 16-Ft Transonic Wind Tunnel blades, moisture changes produced significant stresses in the bolt hole region. The insights gained from these analyses were used to improve the design of the new blades for each of these tunnels.

## Rake and Sweep

Rake and sweep of the blade stacking axis are used to reduce stresses, especially in the root area where generally the stresses are a maximum. Blade centrifugal force is used to offset the bending due to thrust and torque loadings. The stacking axis can be straight or curved. Usually it is deflected only a degree or two. It is important to consider all load cases to ensure that rake and sweep do not cause a significant problem for other cases, especially deceleration or emergency stops where there may be a significant load reversal.

It is more straightforward for fixed pitch fans which use variable rotational speed to vary wind-tunnel airspeed. For these fans the advance ratio is nearly constant. For fans with constant rotational speed and variable pitch or variable inlet vanes, the centrifugal loadings are constant, but the thrust and torque loadings vary over a wide range. In these cases a careful assessment is required and an analysis of the duty cycle is usually required.

## Root/Hub Fairings

Historically, fairings have been a problem for fan systems including those with wooden blades. Fairing failures have caused significant blade damage in the LaRC 16-Ft Transonic Tunnel and the 7- by 10-Ft High Speed Wind Tunnel prior to the recent blade failure. Also ARC has experienced fairing problems for the repowered 40- by 80-Ft Wind Tunnel. These fairing designs range from metallic to composite materials. Wind tunnel fairings in the ARC Low Speed 7- by 10-Ft Wind Tunnel have worked very well. These fairings, built of sheet metal and attached to the hub, are excellent from a structural and aerodynamic viewpoint. The one drawback with these is that many fasteners have to be removed to inspect the blade root area.

Many of the NASA wind tunnels do not use root fairings. The loss of performance for fan systems without fairings is hard to quantify. Generally it is believed to be small (a few percent) but depends on the fan design and loading near the root area (see ref. 23). Fans which are lightly loaded in the root area most likely would not pay as large a penalty as fans highly loaded in the root area. The hub area should be sealed to the extent that undesirable flow effects cannot occur. The hub area should be designed to minimize undesirable recirculation and radial flow but not allow heat buildup near the root.

Based on past experience, where possible, fairings should be eliminated or left off in new designs. It is also recognized that the aerodynamicist will have to be convinced that fairings are not necessary. However if fairings are required, it is extremely important that they be designed and tested to withstand static and dynamic loadings (including both mechanical and thermal), be highly resistant to fatigue damage, frangible to the extent that risks of major blade damage be minimized, and be easily removed for inspection purposes. Generally speaking fairings see very high g loads (some fairings see ~500 g's) during operation and since the fairing c.g. is offset from the blade center line, very high peel loads can result. Experience has shown that bonding fairings to the blades is not effective and mechanical retention is needed for reliability. A factor of safety of 5 on ultimate is desired for the attachment region and vigorous development tests are recommended.

## Fabrication

It is strongly recommended that fabrication be done by those who have successfully constructed wooden propellers, rotors, or fans in the past because expertise and experience are crucial due to the criticality of the fan and the large amount of hand work required. A design and build contract is recommended. During construction good quality assurance is crucial because of woods' variability and its anisotropic structure. In addition, fabrication flaws or errors may not become evident until several years after construction has been completed and the fan has been operated for a number of years. During construction frequent material tests, joint tests, etc., as described in earlier sections of this paper, are mandatory to ensure adequate quality of the wood, glue, and construction. Generally much higher quality standards are required than for normal wood construction because lower factors of safety are used to minimize weight and centrifugal force.

## DRIVE SYSTEM DESIGN CONSIDERATIONS

This section covers design related recommendations which are in addition to others in this document which became evident during the study. Most are also appropriate for all wind-tunnel drives. The design guidelines or recommendations are not intended to be comprehensive but are additional items which were found to be important and worthy of mention.

## Balancing

It is important to balance fans as precisely as practical for smooth operation. All drive elements should be balanced individually prior to their assembly. If possible, dynamic balancing should be done; however, if not practical, carefully done static balancing is acceptable. Provisions should be made for dynamically balancing the entire drive if it appears necessary or as a minimum to verify the balancing process.

A combination of approaches was used for the repowered drive of the 40- by 80-/80- by 120-Ft Wind Tunnel. The motor was dynamically balanced at the motor manufacturer's plant. The fan hub was quite narrow, and it was statically balanced by the fabricator in one plane as per the specification. The center of gravity of each fan blade was individually controlled or adjusted both radially and chordwise. The allowed static moment was less than 100 ft-lb for the fan assembly which weighed about 80,000 lb. The drive operation was very smooth; vibration sensors indicated less than 1 mil peak-to-peak displacement of the drive shaft at the rated rotational speed of 180 rpm.

## Loss of 1/2 of the Blades

If possible the drive system should be designed to withstand the unbalance loads due to the loss of 1/2 of the blades. If foreign objects or other reasons cause loss of the fan blades, the worse-case unbalance is with 1/2 of the blades missing. If the bearings, drive support, drive shaft, etc., can accommodate this unbalance, then damage to the drive is minimized. Otherwise, additional damage to the drive system can cause major expenses and delay. Experience with several NASA wind tunnels has supported this conclusion. Recently mishaps with the Ames 40- by 80-/80 by 120-Ft

Wind Tunnel, the Langley 7- by 10-Ft High Speed Wind Tunnel, and the Langley National Transonic Facility have reinforced this approach.

Some judgment is required as to the weight and dynamic load amplification factor to be used for design; it depends on the fan geometry and arrangement. In the case of the repowered 40- by 80- by 120-Ft Wind Tunnel the unbalance force used was the entire blade weight which included a steel adapter. No dynamic amplification was used, but the weight of half of the blades was used resolved in one direction. Post failure analysis of the Langley 7 x 10 High Speed Wind Tunnel indicated dynamic factors as high as 2 accounted for bending of the drive shaft. See reference 27.

#### Containment Shield

A shield that contains any fan system fragments, etc. in the event of an accident should be considered if penetration of the tunnel wall creates a secondary hazard. The shield may be just a thicker shell at the fan. It should extend at least one blade chord upstream and one chord downstream of the fan tip path plain. Generally for wood fans the thickness required for containment is small. Often for wind tunnels with a steel shell the steel thickness used for normal construction is enough.

#### Interference (Campbell) Diagram

Avoidance of resonance conditions is very important for long life. Use of an Interference Diagram during design is very useful in doing this. There can be several aerodynamic and electrical forcing functions. A sample diagram is given in figure 23. This is for the fan in the LaRC High Speed 7- by 10-Ft Wind Tunnel. Several forcing functions are shown as well as several natural frequencies. Potential resonance points occur at the intersections of the curves. In most cases the forcing functions are very weak at the intersection, so resonance is not a problem. Usually the most important for wooden wind-tunnel fans is the first bending and a once per revolution forcing function (i.e. one per rev curve in the figure). For the example shown, intersection of the one per and first bending mode does not occur.

#### Hub Region Venting

Local areas in or around the hub which can become hotter than the main airstream should be avoided for wooden fans by appropriate venting. The assumption is generally made that the entire fan is at the same temperature as the main airflow, but this may not always be true. Higher temperatures can be caused by the local pumping of air trapped in the hub or nacelle areas. These temperatures can be significantly higher than the mainstream temperature and can reduce the structural capability of the wood in the root area which is usually the critical structural area (see ref. 22).

#### INSPECTION, MONITORING, AND REPAIR

Inspection and monitoring of fan blades are essential to guarding against deterioration, damage, and potential failure during the service life. Recent experiences with wooden fan blade failures as well as historical data on blade failures support the need for greater emphasis on in-service blade inspection and monitoring. Very

little information is available in the literature, however reference 29 contains criteria developed for wood aircraft applications. The following criteria, procedures, and methodology should be employed to the extent possible for all NASA wind tunnels with wooden blades.

### Written Procedures

Written procedures should be developed for all daily, weekly, monthly, yearly, etc., inspections. This includes all inspections ranging from a simple visual inspection to inspections in which blades are removed from the tunnel. Such procedures shall be sufficient in detail to assure that all inspections are done in a specified manner, accomplished by qualified personnel and documented and analyzed according to specified requirements. Checklists should be prepared for all inspections and results formally documented for semi-annual or annual inspections.

### Inspection Personnel

Routine inspections are normally done by personnel assigned to the wind tunnel. Annual or detailed inspections should be performed by personnel specifically trained on methods and procedures for inspection of fan blades and associated hardware (e.g., fairings).

### Inspection Intervals

Inspection intervals are normally established on a daily, weekly, and annual basis. Generally, wind tunnel personnel perform the daily and weekly inspections. However, the annual inspection (usually performed during annual shutdown for maintenance) is considered to be key to identifying major problems. The annual inspection should require the participation of appropriate engineering, research, and NDE personnel. It is recommended the blades be removed for inspection at established annual intervals if the entire blade cannot be otherwise inspected. For example, remove several blades each year and all blades at 5 year intervals for high risk tunnels. This is particularly important for fan blades judged to be in an "occasional" to "frequent" risk category, as evaluated by the use of material in the risk assessment section of this document. Variations on the aforementioned intervals (e.g., every 6 months) should be considered for situations of severe or unexplained blade cracking or much higher than normal run time at high speed.

### Inspection Methods

The following information is offered with respect to methods currently being used or investigated with application to nondestruction examination of fan blades.

Visual/surface. - Visual inspection for cracks is basically an art. Crack detection in wood is a particularly difficult problem since some cracks may not show up unless under load, and the tendency for cracks to open and close depends on the environment, i.e., moisture, and temperature effects. Enhancement of cracks is a particular problem, e.g., dye penetrant does not work very well due to wick action. Often times, a crack or crazing in the fiberglass covering of the blade may indicate cracks in the load-carrying portion of the blade.



Ultrasonic. - Ultra sound techniques are not used for laminated wood since off-the-shelf UT equipment (transducers) are not capable of propagating sound through wood. Because of the high attenuation of sound in wood, broadband transducers are required, which means that transducers and measurement systems would have to be developed. Recent work at LaRC in connection with load tests on a modified root blade attachment for the 16-ft transonic tunnel blades, using state-of-the-art acoustic emission equipment verified the problem with sound attenuation. Selective placement of the transducers on the metal blade attachment fixture did, however, give an indication of load distribution in the blade attach bolts.

Radiographic. - Radiography of wooden structures is hampered by the basic inhomogeneity of the material. Local discrete density changes in the form of earlywood and/or latewood growth bands selectively attenuate penetrating radiation and cause corresponding density variations on the radiographic film image. These local density changes can best be described as a zebra effect and their presence makes interpretation of the radiographic image very difficult. In addition, these base material images tend to mask the presence of other latent defects such as cracks or delaminations.

A technique has been developed at the Langley Research Center (see ref. 30) which has been employed to successfully enhance the image of latent wooden structure defects. This technique utilizes a commercial industrial cleaning solvent Trichlorotrifluoroethane ( $\text{CCL}_2\text{FCCLF}_2$ ) as a radiopaque penetrant. This solvent has a fairly high molecular weight and relatively safe toxicity threshold limit value, especially when compared to more conventional radiopaque materials. The technique entails the radiography of the wooden parts before and after injection of the solvent into surface breaking cracks or delaminations. When the before and after radiographs are reviewed simultaneously, defects are more readily discerned, and sized.

This technique has been successfully used on fan blades from the LaRC 16-Ft Transonic Wind Tunnel and has been used to X-ray the highly loaded attachment holes on the newly installed blades in the LaRC 7- by 10-Ft High Speed Wind Tunnel. These X-rays will be used as the baseline for determining damage in these areas based on future inspections. The main disadvantage of this method is that it requires removal of the blade from the facility.

#### Vibration Testing as a Technique for Verifying/Evaluating Blade Structural Integrity

Vibration testing has long been used for in-place testing of fan blades as a means of testing for evidence of looseness, fatigue damage, etc. However, recent evaluation of this technique in connection with the LaRC 7- by 10-Ft High Speed Wind Tunnel failure (refs. 5 and 31) and the Ames 40- by 80-/80- by 120-Ft Wind Tunnel (refs. 32 and 33), raises questions with regard to the usefulness of such testing.

Typically, vibration records obtained from such tests are examined for changes in frequency as a way of indicating change in blade integrity. Changes in damping is considered to be a better measure of blade deterioration. Examination of records obtained from damaged blades often shows significant change in damping with little or no change in natural frequency.

Based on experiments at LaRC and evaluations of this technique the conclusion seems to be that this technique cannot be relied on to detect subtle changes in the blade structure (e.g., cracking in the blade/hub interface regions) which could re-

sult in blade failure. Further work needs to be done to determine if the technique can be improved or by using a different approach to show that the technique is a good diagnostic tool. However, it is recommended that the procedure continue to be used for the following reasons.

1. Substantiate blade design and manufacturing process (i.e., all blades should have a similar frequency response).
2. Verify installation integrity (e.g., could detect looseness of blade attachment).
3. Verify dynamic design (i.e., mode shapes and frequencies).
4. Track changes in structural response characteristics (e.g., significant changes in damping from one year to the next, see ref. 32, which could aid in selection of particular blades for thorough inspection).
5. Obtain modal data for analysis of blade dynamic response. (NOTE: May be difficult to get higher bending and torsion modes after installation.)

Such measurement/tests should be accomplished as follows:

1. Written procedures should be established for performing the test. (NOTE: In some cases procedure will be tunnel dependent.)
2. Above all, the test should be repeatable, that is, the same procedure should be followed every time, same data acquisition method, same sensor location, etc. This is extremely important because it is the change (say, from year to year) in frequency, damping or some other parameter that is the key to detecting problems.
3. The test should be performed by highly qualified personnel. Preferably an engineer should be designated to oversee such tests.
4. The results of such tests should be documented. Such documentation should include the data, and results of the data analysis and conclusions. This documentation should be routed to the responsible wind-tunnel management/operations personnel and formally reviewed and approved by a designated line manager or chief engineer in the organization responsible for the test.

#### Fan Blade Repair

Wind tunnel fans occasionally suffer from foreign object damage. One very important advantage of wooden fans is that they can be repaired even after relatively major damage, and generally these repairs can be done without removing the blades. It is highly desirable to obtain repair procedures from the blade manufacturer. Construction details such as the covering (or finishing) system vary for different fans and detailed repair procedures are required. If procedures are not available from the manufacturer, references 34 and 35 contain procedures and guidelines for repair of wooden aircraft propellers which may be used for the repair of the wooden structure of the wind-tunnel fans. In general, the procedures given are conservative for wind-tunnel fans; often more extensive repairs than allowed by the reference can be made for wind-tunnel fans. The details in the reference for repairing the covering systems, leading edge protection devices, etc. may not be applicable.

## OUTLOOK FOR FUTURE USE OF WOOD IN FAN BLADE DESIGN

The desirability for continued use of wooden blades was reviewed in light of recent advances in composite technology. Some of the pros and cons (when compared with metal or composites) are as follows:

### PROS

- Lowest cost ( $<1/2$ ) (for appropriate stress and environmental conditions).
- Repairability (quickly and easily repaired in place).
- Foreign object damage is generally not as catastrophic for wooden blades as it is for metal blades. This is important because the probability of major foreign object damage is high regardless of the blade material.
- Life (experience shows 50+ years life is attainable).
- Minimum failure damage to tunnels (blades tend to shatter and splinter rather than fragment and penetrate). This is also true for all-composite blades.
- The relatively high damping capability of wood is good and is important for wind-tunnel fans because all loadings may not be known, and the loadings may be different for different research modes. (High damping is also present for all-composite blades).
- Increasing availability of high quality densified wood laminates.

### CONS

- Limited fabricators (driven by decreasing demand).
- Perception of outdated technology.
- Decreasing availability of quality Sitka Spruce.

Wooden fan blades are a logical choice for subsonic, atmospheric wind tunnels. It is believed that most future NASA tunnels will have more severe operating environments which are not conducive to the use of wooden blades. However, a strong requirement exists for good inspection, analysis, and repair procedures to keep our present stable of wooden fan blade tunnels operating safely.

## NASA WIND TUNNELS BLADE REPLACEMENTS

Recent and planned blade replacements for NASA wind tunnels are listed below.

<u>Year</u>	<u>Wind Tunnel</u>	<u>Location</u>	<u>Material</u>	<u>Comments</u>
1988	7- by 10-Ft High Speed	LaRC	Sitka Spruce	Modified root design (operational)
1989	16-Ft	LaRC	Sitka Spruce/ Compreg	Modified Compreg root area
1990 or 1992	IRT	LeRC	Sitka Spruce	No change in blade design, but additional clamping force is used to reduce stress in attachment region.

## TECHNOLOGY ASSESSMENT AND PROPOSED RESEARCH AND DEVELOPMENT

This section assesses current technology and describes R & D activities which are recommended by the committee in view of both immediate and long-term payoffs for design, fabrication, repair, and inspection of wooden fan blades. These proposed activities are focused primarily on maintaining present fan blade systems and reducing the risk of failure. Also, some of these activities, particularly those relating to inspection methods, have potential high payoff for fan blades made of metallic or composite materials.

### Materials Research

The "Wood Handbook" (ref. 8) and other available publications provide a large data base for wood mechanical properties and accounts for moisture and temperature effects to a large extent. Densified wood "Hydulignum" is thought to be well characterized by the manufacturer but further testing of the material may be warranted.

NASA tunnels operate between -60°F to 200°F with the relative humidity ranging from 0 to 100%, and with exposure times up to 2 or 3 hours. Data available in the literature do not address these extremes. However, there is caution noted in the literature for temperatures above 150°F. Wood may suffer a permanent loss of strength at temperature above 150°F. Therefore, a limited test program is needed to determine the mechanical and fracture and fatigue properties of Sitka Spruce and densified wood at -60°F and +200°F for increasing cycles of exposures to these temperatures for 2 hours duration.

Of particular interest is the future development of fracture properties which may be used in analytical procedures for predicting crack growth to failure. Theoretical development of analytical codes or use of existing codes for predicting crack growth should be coupled with laboratory testing to establish such capability.

The committee supports the implementation of a limited test program as described above. However, it is felt that more emphasis should be placed on grading wood properties (see ref. 35) as opposed to a major material properties test program which in the end would add very little significant information to the data base.

Fatigue tests.- Fatigue tests of pin loaded specimens are needed to understand the initiation and growth of shear cracks. Experience has shown that blade shear out is the primary mode of failure, however, the validity of using existing analytical codes for predicting failure should be established. Also, such tests would be valuable for identifying specific regions of the attachment holes that are critical and should be inspected closely. The committee strongly recommends that this type of testing be initiated as soon as possible. Such tests should include both laminated Sitka Spruce and the densified Hydulignum material.

#### Nondestructive Examination

Radiographic inspection enhancement.- Recent work at the NASA LaRC (see ref. 30) indicates that radiographic (X-ray) inspection can be enhanced significantly by subjecting the blade to liquid freon. This technique is discussed previously in the Inspection Methods section of this report. This work looks very promising and the committee recommends that the work continue and be documented for dissemination at all facilities using wooden fan blades.

Computer tomography.- Computer tomography (CT) is a 3-D imaging process which uses an X-ray source to reveal variation in density or structure either statically or under load.

At present, there is an on-going program at NASA LaRC to develop a CT high resolution system for inspecting small structural volumes. Discussions with the principal investigator indicates that a second system can be built which would have a resolution of the order of 1 mm and could be used for CT mapping of fan blades.

The chief advantage of such a system is that 3-D mapping can detect cracks as well as map cracks growing under load for any kind of geometry. The principal disadvantage is that the blade(s) would have to be removed from the tunnel(s) and shipped to the laboratory for inspection. The system resource requirements is estimated at ~\$900K with a delivery time of ~2 1/2 years. The potential payoff would represent a quantum jump in NDE technology and could be used for all types of fan blades including metallic and composites. It is recommended that program support be provided to do a feasibility study for building such a system.

Acoustic emission.- Acoustic emission has been used extensively in metallic materials for detecting crack growth. However, because of the high sound attenuation in wood, present technology does not exist to do quantitative measurements, i.e., current transducers\* cannot be used. Broadband transducers are required and would be very large compared to current ones. However, it is believed that technology for using acoustic emissions for laminated wood can be developed and has a high payoff

\*Recent tests at LaRC using acoustic emission to detect damage in a redesigned butt section for the 16-ft tunnel blade undergoing load tests demonstrated that state-of-the-art equipment cannot detect sound emissions in wood. The tests, however, did give information relative to the distribution of loading at the bolt attachment (metallic component emissions).

potential. It is, therefore, recommended that a feasibility study be conducted to determine if such a program is viable.

### Monitoring Structural Integrity

Tip clearance.- Changes in tip clearance could signal eminent failure of a fan blade(s). It is recommended that developmental work be initiated to study methods for measuring tip clearance during operation using such possible techniques as eddy current, capacitance, Hall effect and/or other types of sensors. Some work has been done at LaRC; see the section on Frangible Tips and Tip Clearance in this paper. This work is endorsed by this committee.

On-line structural integrity.- Various types of devices have been considered for monitoring structural response which could give an indication of damage and/or impending failure. These include noise spectra (signature), strain gages, fiber optic devices embedded in the blades, etc. However, the principal problem in using any type of sensor is locating it in the critically loaded part(s) of the blade (e.g., around bolt attach holes). The use of such devices presents many problems related to design, development testing, and manufacturing. However current work in hypersonic aircraft structures and advanced launch systems technology is aimed at designing and developing such techniques which could result in so-called "smart" structures. Payoffs from these technology activities could prove useful in their applications to wooden fan blades.

### CONCLUSIONS AND RECOMMENDATIONS

This paper presents information compiled by the Inter-Center Committee on Structural Integrity of Wooden Fan Blades, and is intended as a guide for use in design, fabrication, evaluation and assurance of NASA fan systems using wooden blades. The information can be of significant value to fan blade designers, fabricators, inspectors, wind-tunnel operations and safety personnel as well as facility managers. Wood is an excellent material for wind tunnel fan blades if the design is reasonably conservative. State-of-the-art information is provided for wooden fan blade design, inspection, monitoring, and repair. Additionally, drive system design considerations are provided which are based on current practice and experience.

Based on the findings of this committee the following recommendations are offered:

(1) This report should be disseminated to the OAST Centers engineering, fabrication, inspection, and wind-tunnel research and operations personnel.

(2) This document should be used as a guide for establishing NASA/Center policy on issues relating to continued safe operation of new and/or existing wind tunnels utilizing wooden fan blades.

(3) A risk assessment (using the method provided in this paper or an alternative approach) should be considered and appropriate actions taken if the fan blades are judged to be a high risk.

(4) All wind tunnels should have spare blades. Commensurate with the risks, those tunnels characterized as having a "frequent" failure risk should have a full set of spare blades. In addition for critical and unique facilities of national

importance which are heavy in demand, there should be a full set of spare blades to minimize the shutdown period in the event of a mishap.

(5) Heavy emphasis should be placed on instituting a formalized blade inspection and structural integrity evaluation plan for all wind tunnels with wooden blades.

(6) The proposed research and development activities described in this paper should be further evaluated and funding provided for implementing those programs judged to be most promising.

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## APPENDIX A

### SPARE PROPELLER BLADE SURVEY\*

Survey forms were distributed to the operators of major wind tunnels, worldwide, at the Subsonic Aerodynamic Testing Association (S.A.T.A.) Conference in Los Angeles, February 15, 1979, by Mr. S. B. Wallis of Ford Motor Company. The survey attempted to determine how many facilities kept spare fan blades and how many had experiences which justified the cost of spares.

The survey was extremely difficult to analyze. The sample size of common variables was too small for a good statistical analysis, however, it was about two-thirds of the facilities represented by SATA. The causes and severity of each accident varied widely. Also, the time in service and the purpose of each tunnel varies. It is difficult to equate the probability of an accident having occurred in a new facility with one that has been in operation for 30 to 40 years.

The circumstances for acquiring spares vary. Some facilities used surplus aircraft propellers with readily available spares. Some made spares after having their first accident. Others delayed buying spares several years to decrease the initial expenditure.

The following variables were analyzed:

- Number of facilities which do or do not have spares available.
- Probability of having accidental damage to the propeller.
- Affect of spare blades on downtime following an accident.
- Affect of blade material on accident rate.
- Probable causes of accidents.

#### Survey Results-Spare Propeller Blades

35 facilities responded.

25 wind tunnels (76%) do have spare blades

- 8 do not have spares (2 of these are ordering spares).
- 6 have less than a complete set.
- 15 have at least one complete set, but less than two.
- 4 have two or more complete sets.

28 accidents have occurred ranging from minor to major (complete destruction).

- 19 accidents classed as "serious"
- 11 accidents classed as "complete wipe out" or damaged beyond repair of blades.
- Nearly all report minor nicks which are generally repaired in place.
- Generally those with metal blades replace them at regular intervals for metal fatigue problems before failures occur.

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\*Permission to include this information in this report granted by S.A.T.A.

Of 14 major accidents, the downtime for repairs were:

- 4 without spares at time of accident: 6-12 months downtime.
- 10 with replacement spares: 0-4 months downtime.

#### Wood Versus Metal/Composite Blading

Of the 33 facilities:

- 20 facilities reported using wooden fan blades.
- 13 use metal or composite blades.

Disregarding the minor nicks and dents which nearly all reported:

- Wood fan blades have suffered a 45% accident rate (9 accidents out of 20 facilities).
- Metal or composite blades have had a 77% failure rate (10 accidents out of 13 facilities).

#### Causes of Accidental Damage

Of the 9 accidents with wooden fan blades:

- 4 were failures of blade root attachment into metal.
- 1 was caused by dry rot.
- 1 was caused by corrosion of metal attachment.

These 6 cases should not be classed as accidents but rather as design problems or neglect of maintenance.

The remaining 3 cases were described as accidental:

- Model moved downstream (foreign object damage).
- Bumped by crane during maintenance.
- "Uncertain" cause but modest damage.

3 accidents to wood blades out of 20 facilities is a 15% failure rate.

Of the 10 accidents with metal or composite blades:

- 4 were caused by hub failure.
- 2 were caused by blade fatigue.
- 3 were caused by foreign object damage.
- 1 "Uncertain" cause.

#### SUMMARY OF SURVEY

The survey suggests an 85% chance of some form of accident (28 accidents out of 33 facilities) with a 33% chance of a major severity accident (11 out of 33 facilities). Over 75% of the wind tunnels do have one or more spare blades to limit the downtime in case of a severe loss; most had at least a full set of spare fan

blades. Protective screening and break-away tips can minimize damage but cannot ensure risk free operation.

A comparison of wood blades with metal blades indicates the metal blades suffer nearly twice the accident rate of the wooden blades, primarily due to metal fatigue in the blade or blade attachment.

Further analysis of the causes of the failures indicates the wooden propeller, securely fastened at its root and protected from excessive moisture changes, can have a fairly low (15%) probability of accidental damage.

**Table I**  
**Description of NASA Wind Tunnel**  
**Wooden Fan Blade Systems**

Wind Tunnels	H.P.	Fan Dia. ft.	No. of Fans or Stages	No. of Blades per Fan	Max. RPM	Tip Speed ft/sec.	Blade Weight lbs.	Blade Material	Root Stress/PSI	Attach Geometry	Max/Min Temp. °F	Sealant	Tip Clearance In.	Leading Edge Protection
<b>LaRC</b>														
20'	1,300	20.84	1	3	600	763	276	Sitka Spruce	534	Bolted [5]	Ambient	Paint	1/3	Celastec
12'	280	15.5	1	6	650	527	98.4	Sitka Spruce	435	Bolted [5]	Ambient	Fiberglass	1/4	Celastec
30'x60'	4,000/Fan	36	2	4/Fan	293	545	563	Sitka Spruce	296	Bolted [5]	Ambient/+20° F	Fiberglass	3/4	Celastec
14'x22'	8,000	40	1	9	275	576	683	Sitka Spruce	410	Bolted [4]	Ambient/+10°F	Fiberglass	1/4	Fiberglass
16'	60,000	34	2	25 Front 26 Rear	372	668	540	Sitka Spruce/w Hydulgnum	450 Front 418 Back	Bolted [9]	Ambient/+60°F	Fiberglass	1/4	Celastec
7'x10'	14,000	28.9	1	18	490	773	465	Sitka Spruce	580	Bolted [4]	Ambient/35°F	Fiberglass	3/8	Celastec
<b>ARC</b>														
7'x10'	1,800	28.8	1	8	310	471	220	Sitka Spruce	120	Bolted [5]	130/20	Fiberglass	3/4	Fiberglass
7'x10'	1,800	28.8	1	8	310	471	220	Sitka Spruce	120	Bolted [5]	130/20	Fiberglass	3/4	Fiberglass
<b>Old</b>														
40'x80'	6,000/Fan	40	6	6	290	607	782	Sitka Spruce	300	Bolted	140/30	Fiberglass	3/4	Fiberglass
40'x80'x120'	22,500/Fan	40	6	15	180	377	500	Compressed Birch, Sitka Spruce, Balsa Wood	493	Tapered Thread	130/20	Fiberglass	1 5/8	Fiberglass
<b>LeRC</b>														
IRT	5,000	25.4	1	12	460	612	250	Sitka Spruce	552	Bolted [4] & Clamping	100/-20			Hardwood & Rubber

Ambient = 30°F to 120° F

**Table II**  
**Probability of Failure Assessment Worksheet**

	RISK ASSESSMENT FACTOR			WGT. FACTOR	LANGLEY						AMES		LEWIS
					1	2	3	4	5	6	7	8	9
	5	3	1		20'	12'	30'x60'	14'x22'	16'	7'x10'	7'x10'	40'x80'x120'	IRT
Stress Ratio $\frac{\sigma}{\sigma_{ALLOW}}$	>.7	.5	<.3	33									
°F Temperature Variations	>150 <-20	140-120 0-20	32-100	2									
Dynamic Loads	H	M	L	2									
Moisture Barrier Sealant	Poor	Fair	Good	5									
Moisture Environment	Damp $\Delta T > 100^{\circ}F$	Damp $\Delta T \approx 50$	Dry	5									
Bolt Attachment Angle $\beta$ and Shearout Mode	<30° Single Mode	<30° Multiple Mode	>30° None	33									
Airfoil to Root Transition	Short	Medium	Long	10									
Length of Service	>15 Yrs	10 Yrs	<5 Yrs	2									
Visual Appearance of Blades	Poor	Fair	Good	8									
Probability of Failure													

Probability of Failure =  $\Sigma \frac{\text{Risk Assessment Factor} \times \text{Wgt. Factor}}{100}$

Frequent 4-5  
Occasional 3-4  
Possible 2-3  
Remote 1-2

**Table II - A**  
**Probability of Failure Assessment for NASA**  
**Wooden Fan Blade Systems**

	RISK ASSESSMENT FACTOR			WGT. FACTOR	LANGLEY						AMES		LEWIS	
					1	2	3	4	5	6	7	8	9	
	5	3	1		20'	12'	30'x60'	14'x22'	16'	7'x10'	7'x10'	40'x80'x120'	IRT	
Stress Ratio $\frac{\sigma}{\sigma_{ALLOW}}$	>.7	.5	<.3	33	2.5	2.3	1.3	3	3	4	1	Old 1	New 1	1
°F Temperature Variations	>150 <-20	140-120 0-20	32-100	2	1.5	1.5	2	2	5	5	3	3	3	5
Dynamic Loads	H	M	L	2	1.5	2	3	3.5	4.5	2.5	1	5	3	2
Moisture Barrier Sealant	Poor	Fair	Good	5	4.5	3.5	3	2.5	.5	1.2	3	3	1	5
Moisture Environment	Damp ΔT >100°F	Damp ΔT ≈ 50	Dry	5	5	5	5	5	5	5	1	1	1	4
Bolt Attachment Angle β and Shearout Mode	<30° Single Mode	<30° Multiple Mode	>30° None	33	3.5	2.5	3	3	3	5	1	1	1	5
Airfoil to Root Transition	Short	Medium	Long	10	3	2.5	2	3.5	1.5	2	1	1	1	2
Length of Service	>15 Yrs	10 Yrs	<5 Yrs	2	5	5	5	4.5	1.5	1	5	5	1	5
Visual Appearance of Blades	Poor	Fair	Good	8	4	1.5	3	1.5	1	1	1	3	1	5
	Probability of Failure				3.2	2.5	2.4	3	2.7	3.7	1.2	1.2	1.3	3.3

Probability of Failure =  $\sum \frac{\text{Risk Assessment Factor} \times \text{Wgt. Factor}}{100}$

Frequent 4-5  
Occasional 3-4  
Possible 2-3  
Remote 1-2



**TABLE III - MECHANICAL PROPERTIES**

	<i>Tension, PSI</i>		<i>Compression, PSI</i>	<i>Shear, PSI</i>	
	Grain	⊥ Grain	Grain	Normal	Tangential
<i>70° F</i>					
<b>Sitka Spruce, 8% M.C. Hydulignum (1) &amp; (2)</b>	<b>11,986</b>	<b>419</b>	<b>6,897</b>	<b>(3)</b>	<b>1,269</b>
<b>0% Crossply (4)</b>	<b>30,085</b>	<b>(3)</b>	<b>17,135</b>	<b>5,975</b>	<b>3,324</b>
<b>25% Crossply (5)</b>	<b>30,453</b>	<b>11,718</b>	<b>15,959</b>	<b>6,676</b>	<b>1,767</b>
<b>50% Crossply (5)</b>	<b>21,975</b>	<b>19,529</b>	<b>13,842</b>	<b>8,444</b>	<b>1,682</b>
<i>200° F</i>					
<b>Sitka Spruce, 8% M.C. Hydulignum (1) &amp; (2)</b>	<b>6,592</b>	<b>230</b>	<b>3,793</b>	<b>(3)</b>	<b>698</b>
<b>25% Crossply (6)</b>	<b>21,691</b>	<b>7,529</b>	<b>13,235</b>	<b>4,769</b>	<b>2,000</b>

(1) Minimum Values

(2) Minimum of 5 Specimens

(3) Data Not Available

(4) Source - Product Literature

(5) Source - Certification Test Report

(6) Source - In-House Test Report

TABLE IV

## Allowable Stress for Sitka Spruce as Developed for the LaRC 16 Ft. Tunnel Blades

Mechanical Property	Clear Wood Strength Value, Psi	Strength @ 12% Moisture Content, Psi	Strength @ 8% Moisture Content, Psi	Adjustment Factors							Effect of Temperature	Allow Stress, Psi
				Factor for Specific Gravity	Strength Ratio	Duration of Load Factor	Man. & Use	Stress Concentration	End Position	1/d		
F <sub>b</sub> - Extreme fiber in bending	5660 <sup>(1)</sup> 3549 <sup>(2)</sup>	(1.81) <sup>(3)</sup> 10,245 6424	(1.17) 11,986 7516	(1.00) 7516	(.54) 4058	(.70) 2841	(.77) 2188	(1.00) 2188	(1.00) 2188	(1.00) 2188	(1.00) <sup>(4)</sup> (.55) <sup>(5)</sup>	2188 1203
F <sub>t</sub> - Tension II to grain	5660 3549	(1.81) 10,245 6424	(1.17) 11,986 7516	(1.00) 7516	(.36) 2706	(.70) 1894	(.77) 1458	(1.00) 1458	(1.00) 1458	(1.00) (.55)	(1.00) (.55)	1458 802
F <sub>c</sub> - Compression II to grain	2670 1549	(2.10) 5670 3253	(1.23) 6897 4001	(1.00) 4001	(.69) 2761	(.67) 1850	(.80) 1480	(1.00) 1480	(1.00) 1480	(1.00) 1480	(1.00) (.55)	1480 814
F <sub>t</sub> - Tension I to grain	250 168	(1.51) 378 254	(1.11) 419 282	(1.00) 282	(.50) 141	(.70) 99	(.89) 88	(1.00) 88	(1.00) 88	(1.00) 88	(1.00) (.55)	88 48
F <sub>c</sub> - Compression I to grain	279 279	(2.07) 578 578	(1.18) 681 681	(1.00) 681	(1.00) 681	(1.16) 791	(.91) 719	(1.00) 719	(.67) 482	(1.00) 482	(1.00) (.55)	482 265
F <sub>v</sub> - Horizontal shear II to grain	757 510	(1.51) 1143 770	(1.11) 1269 855	(1.00) 855	(.50) 427	(.70) 299	(.89) 266	(.44) 117	(1.00) 117	(1.00) 117	(1.00) (.55)	117 64
E - Modulus of elasticity	1.2x10 <sup>6</sup>	(1.27) <sup>6</sup> 1.6x10 <sup>6</sup>	(1.07) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.00) <sup>6</sup> 1.7x10 <sup>6</sup>	(1.06) <sup>6</sup> 1.8x10 <sup>6</sup>	(1.00) (1.00)	1.8x10 <sup>6</sup> 1.8x10 <sup>6</sup>

- (1) Average Strength  
 (2) 1% Strength  
 (3) ( ) Adjustment Factor

- (4) 70° F  
 (5) 180° F

# TABLE V - DESIGN LOAD CASES (Concluded)

Cause or Condition	Constant	Transient		Steady State		Comments
		Inertia Torque	AERO	Mech/ Elect.	AERO	
Turning Vanes Overturn Underturn					≥ 1P	
Drive Shaft Wake for External Motors					≥ 1P	
Fan Contraction Circular Cross-Section Square to Circle Trans.					AS AP	
Nose Cone & Supports					AS NP	
IGV or Stator Wakes					NP	IGV's or Stators for Multi-Stage Fans
EGV					NP	Usually Flow Angle Distortion
Drive Supports Fan Downstream Fan Upstream					NP	Wake Caused Potential Flow Caused
Off Design Blade Angle Setting		x			AS	Variable Pitch Fans or VC IGV's; Off-Design Loading Distributions

AS - Asymmetric  
IP - Once per Rev  
NP - N Times per Rev.

BL - Boundary Layer  
WT - Wind Tunnel  
EGV - Exit Guide Vanes

IGV - Inlet Guide Vanes  
VC IGV - Variable Camber IGV's

# TABLE V - DESIGN LOAD CASES

Cause or Condition	Constant	Transient		Steady State		Comments
		Inertia Torque	AERO	Mech/Elect.	AERO	
Starting		x				
Normal Controlled Accel. Decel.		x	x			Depends on Rate of Change of Airspeed Controls
Emergency or Fast Stop Open-Circuit Coast Down Dynamic Braking Aerobrakes Drive Shaft Braking		x	x			Large Load Reversals Can Occur
Transferring Frequency of Input Electric Power		x				Variable Freq. Power to Constant Freq. Power & Back
Pulses due to Solid-State Power Supplies		x		x		Can be Especially Bad at Low Speeds
Model Support Wakes					≥ 1P	
Wind Tunnel Growth Boundary Layer					A6, ≥ 1P	Symmetrical for Single Fan W.T.'s ≥ 1P for Multi-Fan W.T.'s
Diffusser Problems Poor design Model induced					≥ 1P	

AS - Asymmetric  
IP - Once per Rev  
NP - N Times per Rev.

BL - Boundary Layer  
WT - Wind Tunnel  
EGV - Exit Guide Vanes

IGV - Inlet Guide Vanes  
VC IGV - Variable Camber IGV's

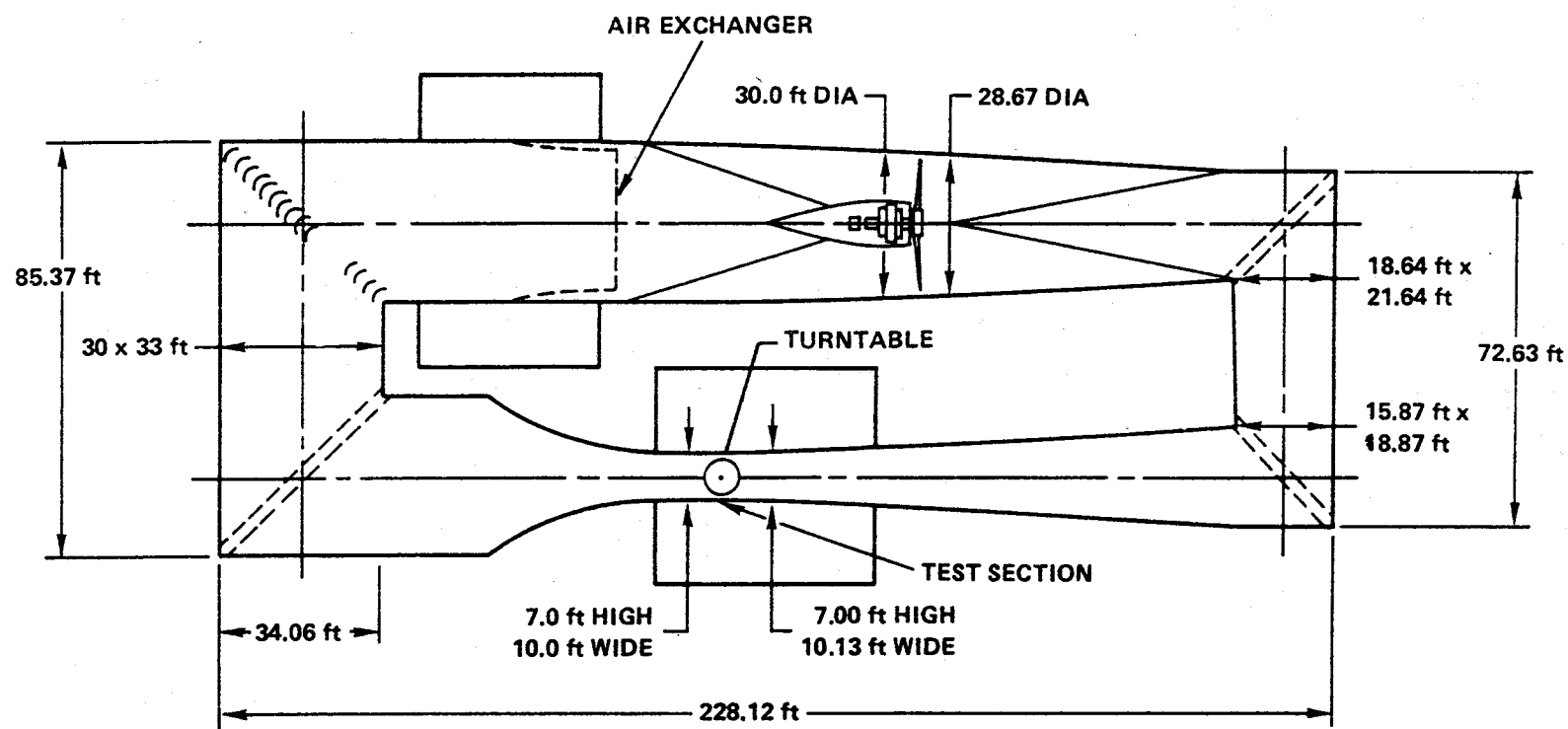


Figure 1. - NASA Ames Research Center - 7- by 10-Foot Subsonic Wind Tunnel

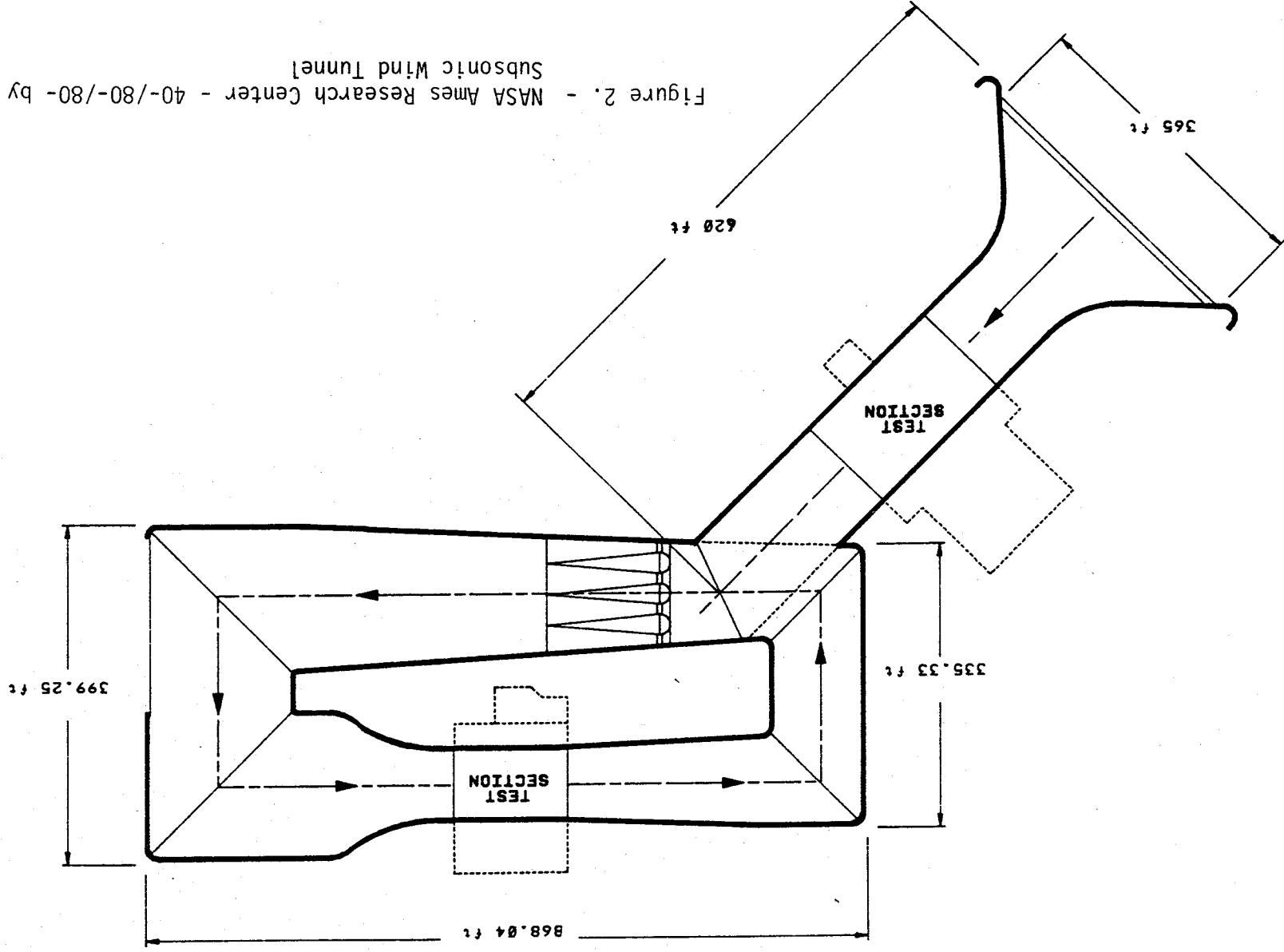


Figure 2. - NASA Ames Research Center - 40-/80-/80- by 120-Foot Subsonic Wind Tunnel

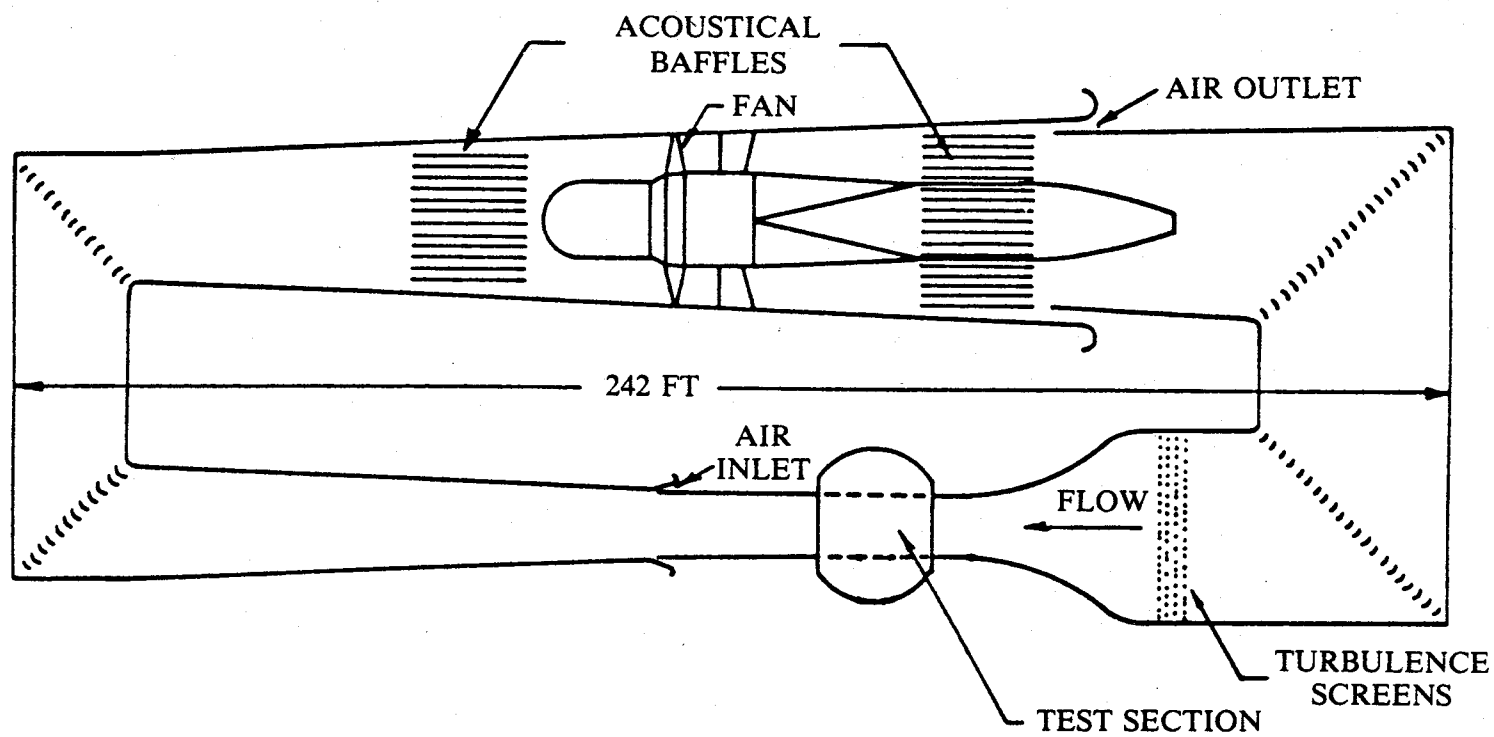


Figure 3. - NASA Langley Research Center  
High Speed 7- by 10-Foot High Speed Wind Tunnel

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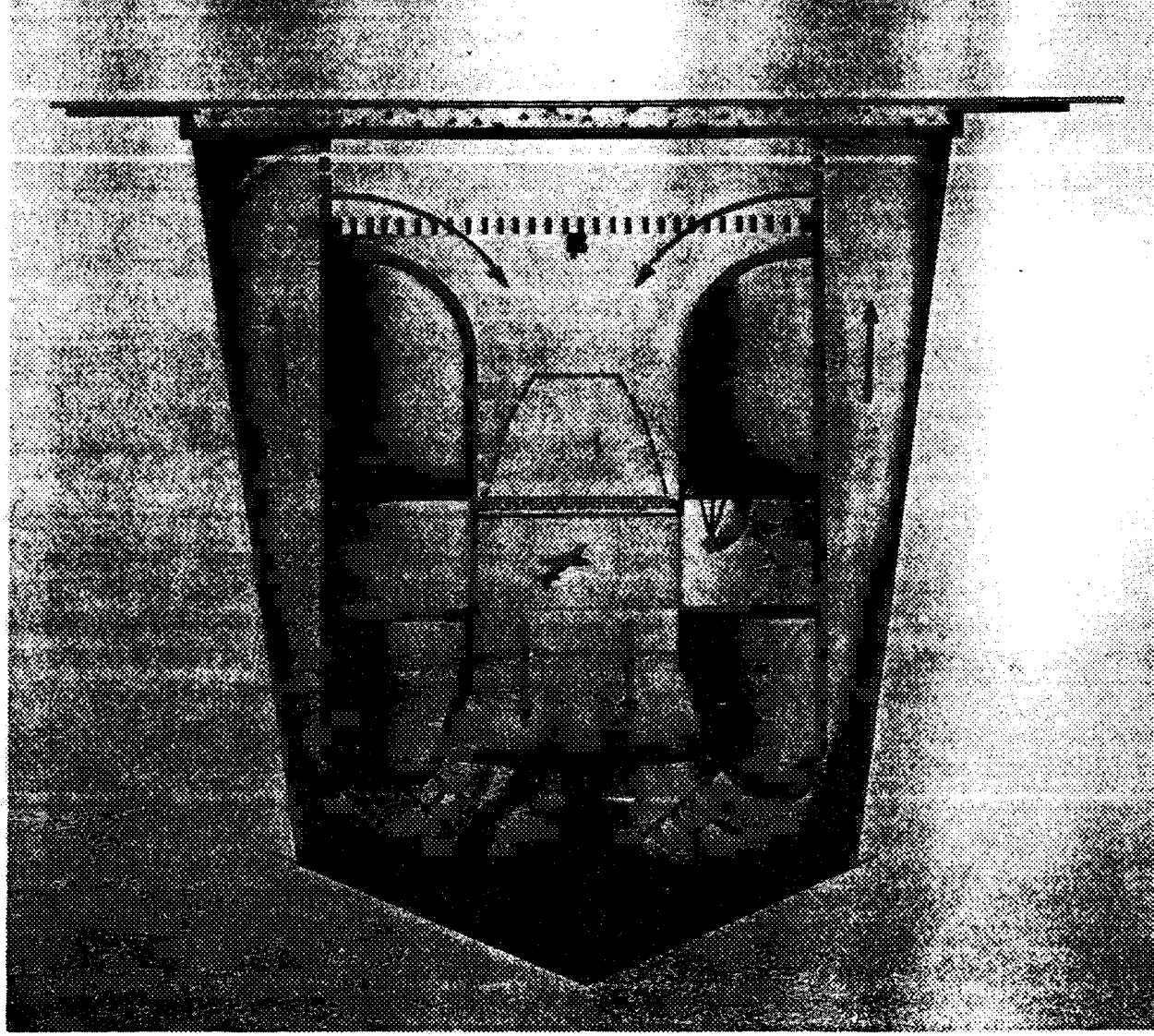
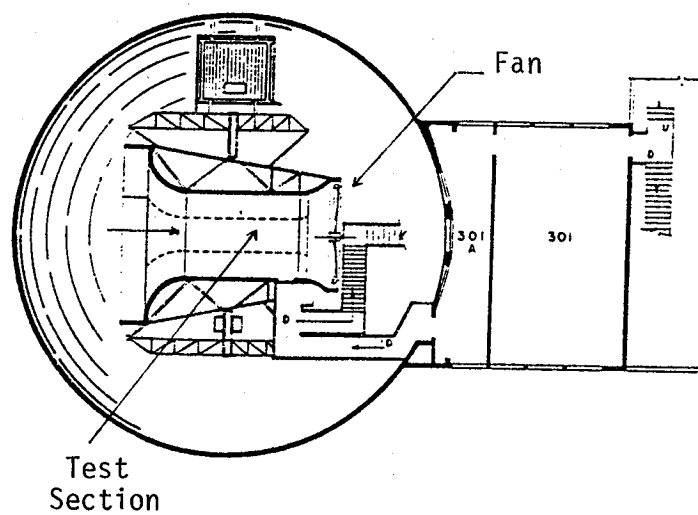
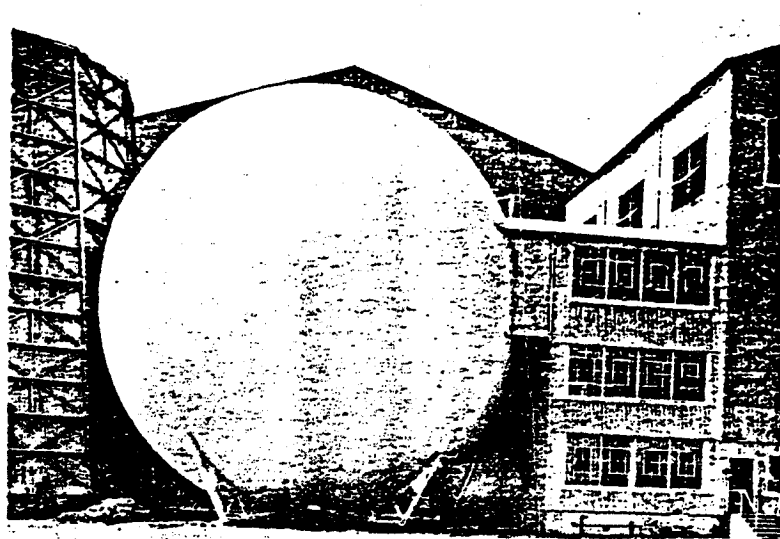


Figure 4. - NASA Langley Research Center 20-Foot  
Vertical Spin Wind Tunnel



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THIRD FLOOR PLAN

Figure 5. - NASA Langley Research Center  
12-Foot Low-Speed Wind Tunnel

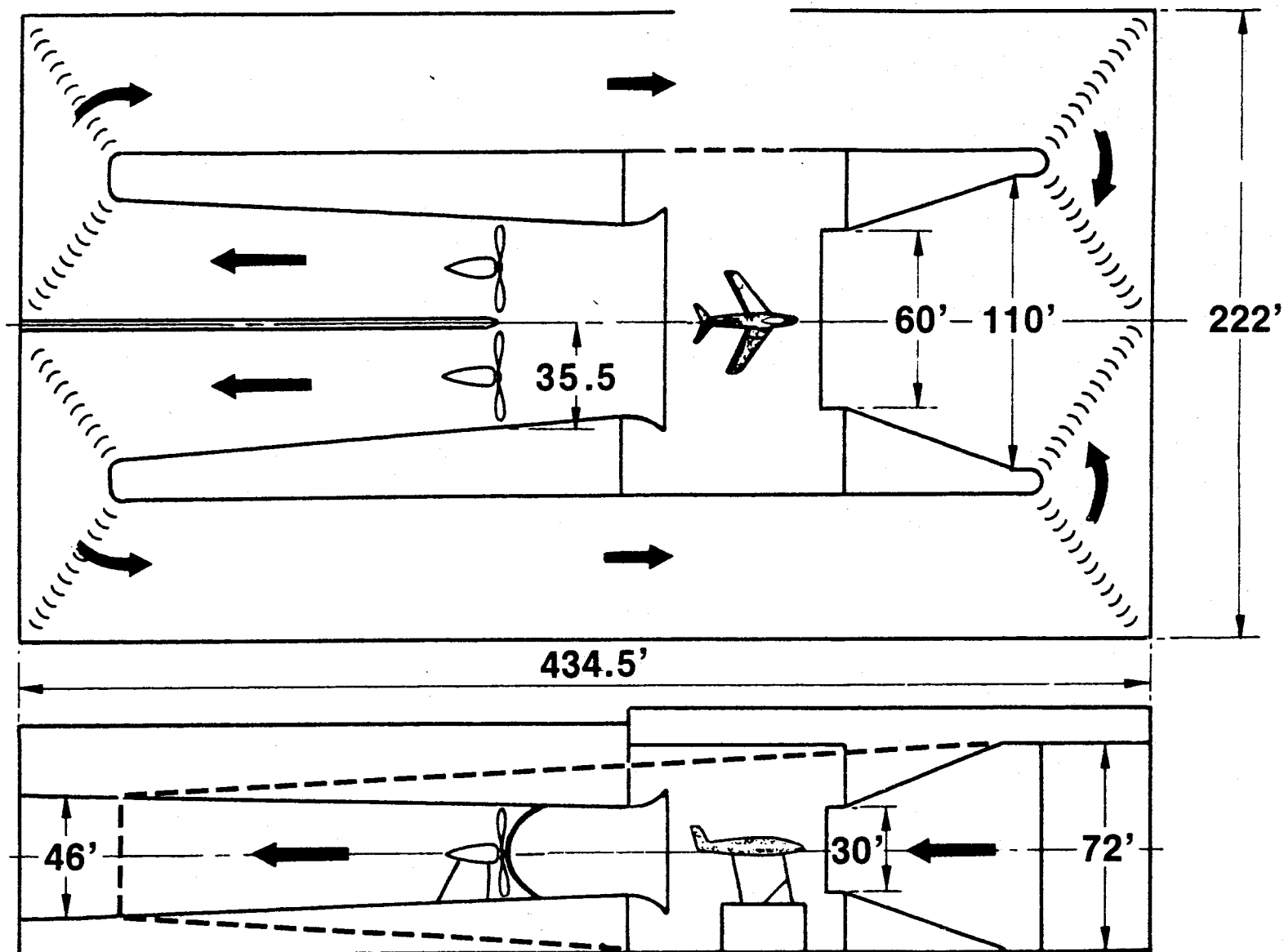


Figure 6. - NASA Langley Research Center  
30- by 60-Foot Wind Tunnel

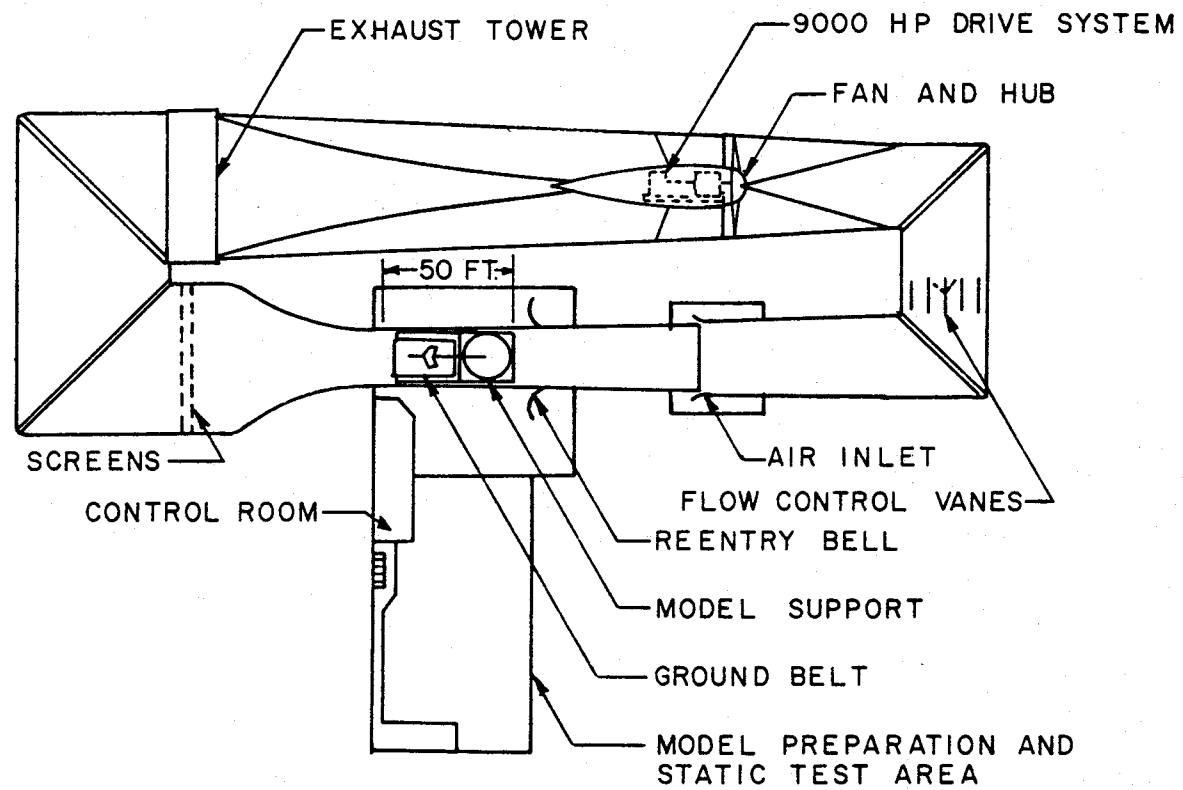


Figure 7. - NASA Langley Research Center  
14- by 22-Foot Subsonic Wind Tunnel

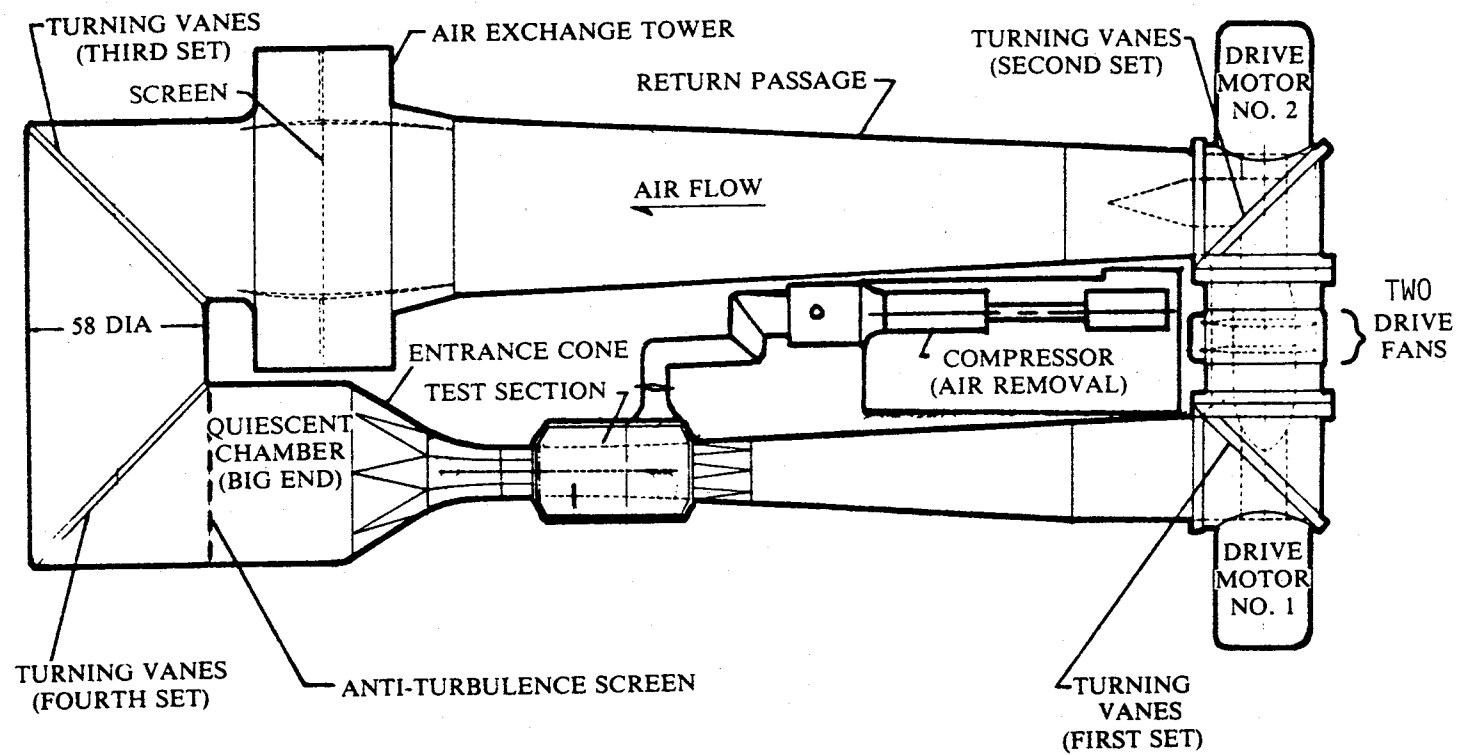


Figure 8. - NASA Langley Research Center  
16-Foot Transonic Wind Tunnel

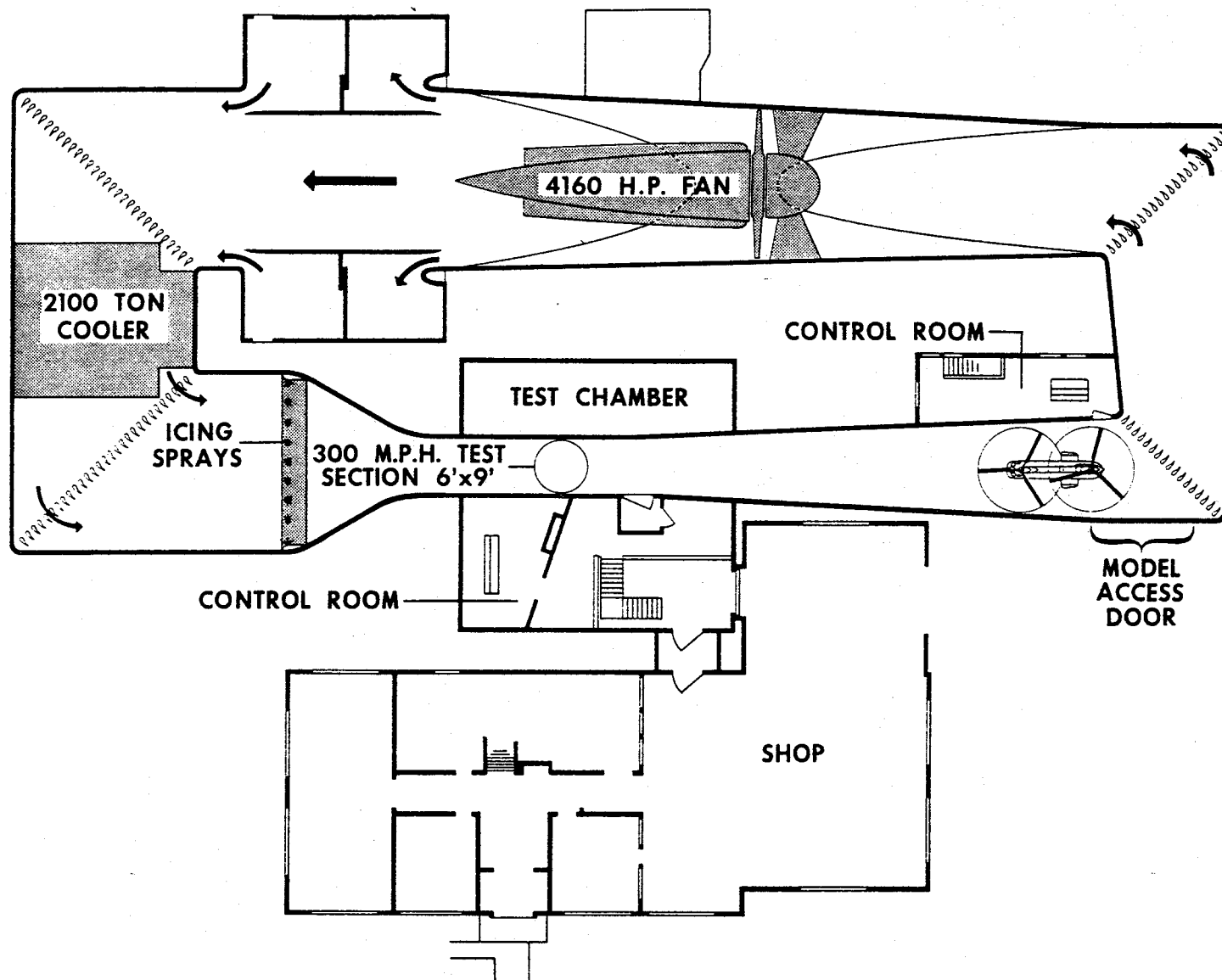


Figure 9. - NASA Lewis Research Center Icing Research Tunnel

## Hazard Probability Definitions

## Numerical Ranges Assigned

The probability that a hazard will occur during the planned life expectancy of the system. The probability level is qualitative based upon engineering judgment with appropriate guidelines as follows:

Frequent - Likely to occur frequently. This is the worst case for no or inadequate mechanical or electrical interlocks, and standard operating procedures to preclude a mishap from occurring.

4-5

Occasional - Likely to occur sometime in life of item. This is the lowest level given if there are no or inadequate mechanical means or electrical interlocks to preclude a mishap from occurring but there are approved standard operating procedures for operators to use.

3-4

Reasonably Probable - Unlikely to occur but possible. This is the lowest level given to electrical interlocks when they are adequate preclude the mishap from occurring.

2-3

Remote - So unlikely, it can be assumed that this hazard will not be experienced. Used when there is a positive mechanical means or there are adequate electrical interlocks and procedures to preclude a mishap from occurring.

1-2

Figure 10. - Hazard Probability Definitions and Numerical Ranges assigned for use with Table II

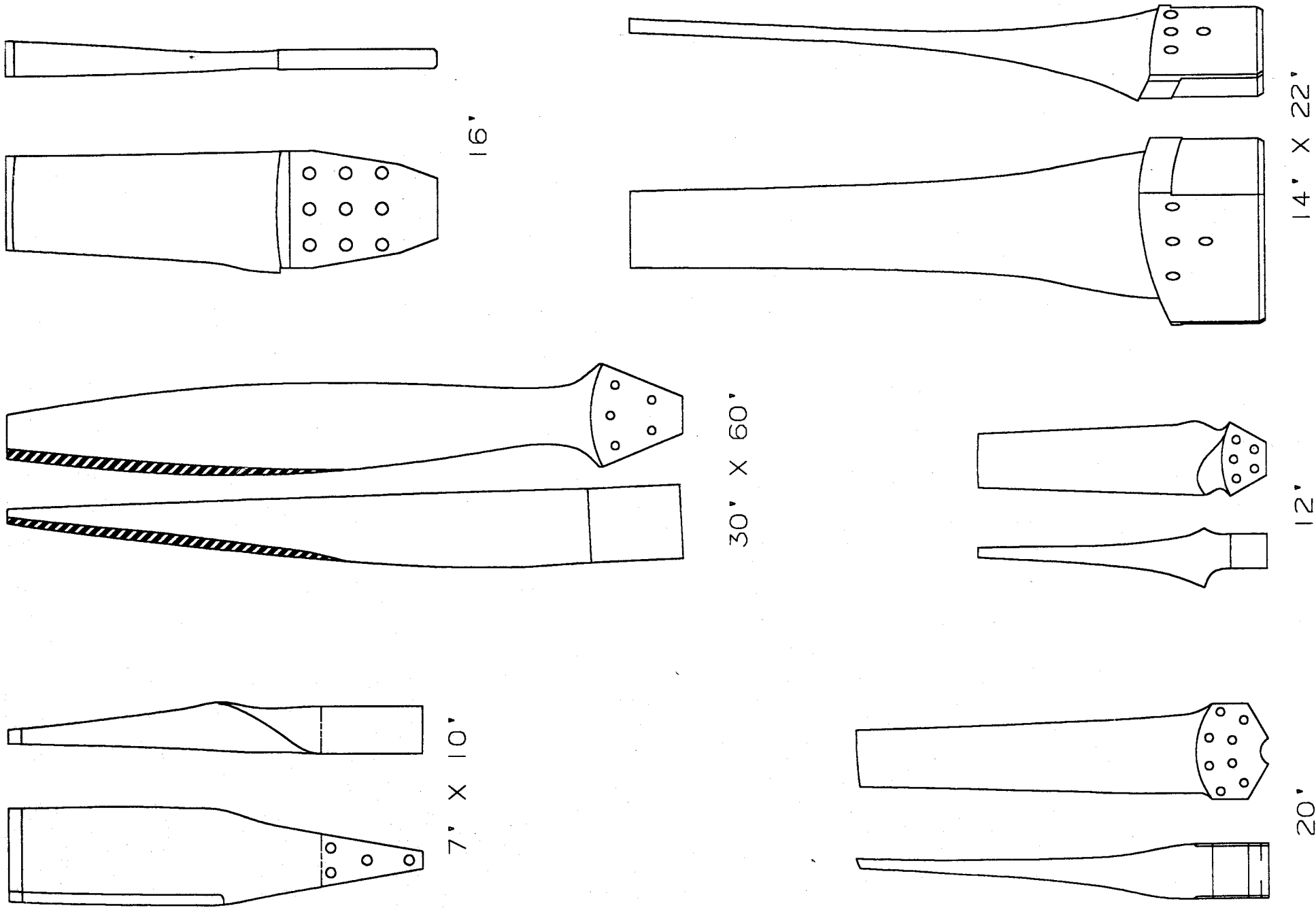
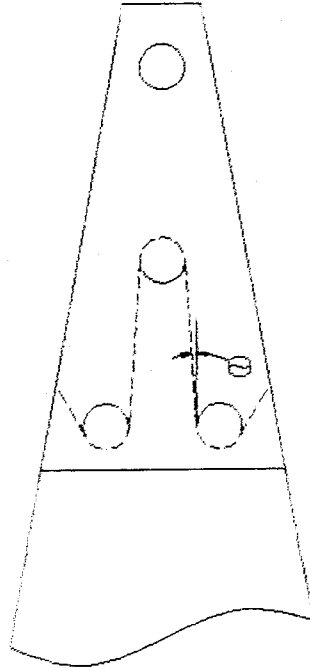
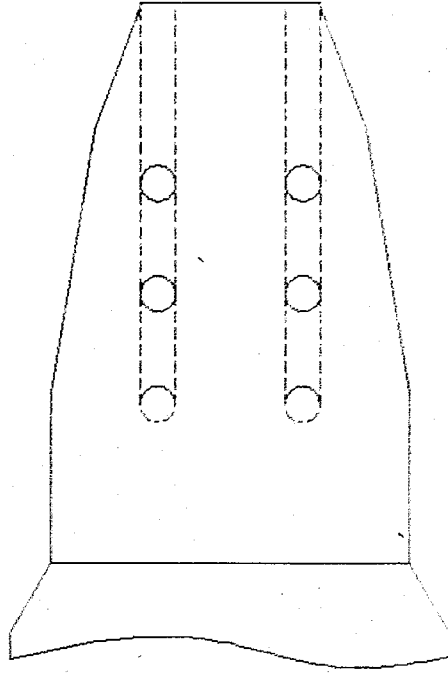


Figure 11. - LaRC Wind Tunnel Fan Blades Illustrating Hub Attachment Geometries

SINGLE MODE



DOUBLE MODE



MULTIPLE MODE

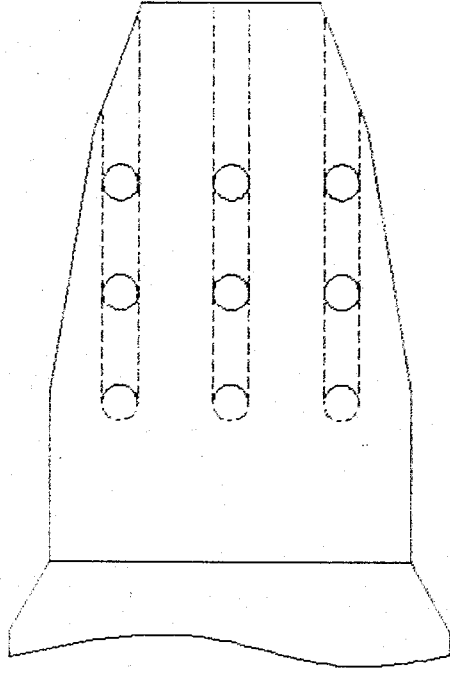


Figure 12. - Hub Attachment Geometries Illustrating Shear-Out Failure Modes  
for Different Bolt Hole Patterns



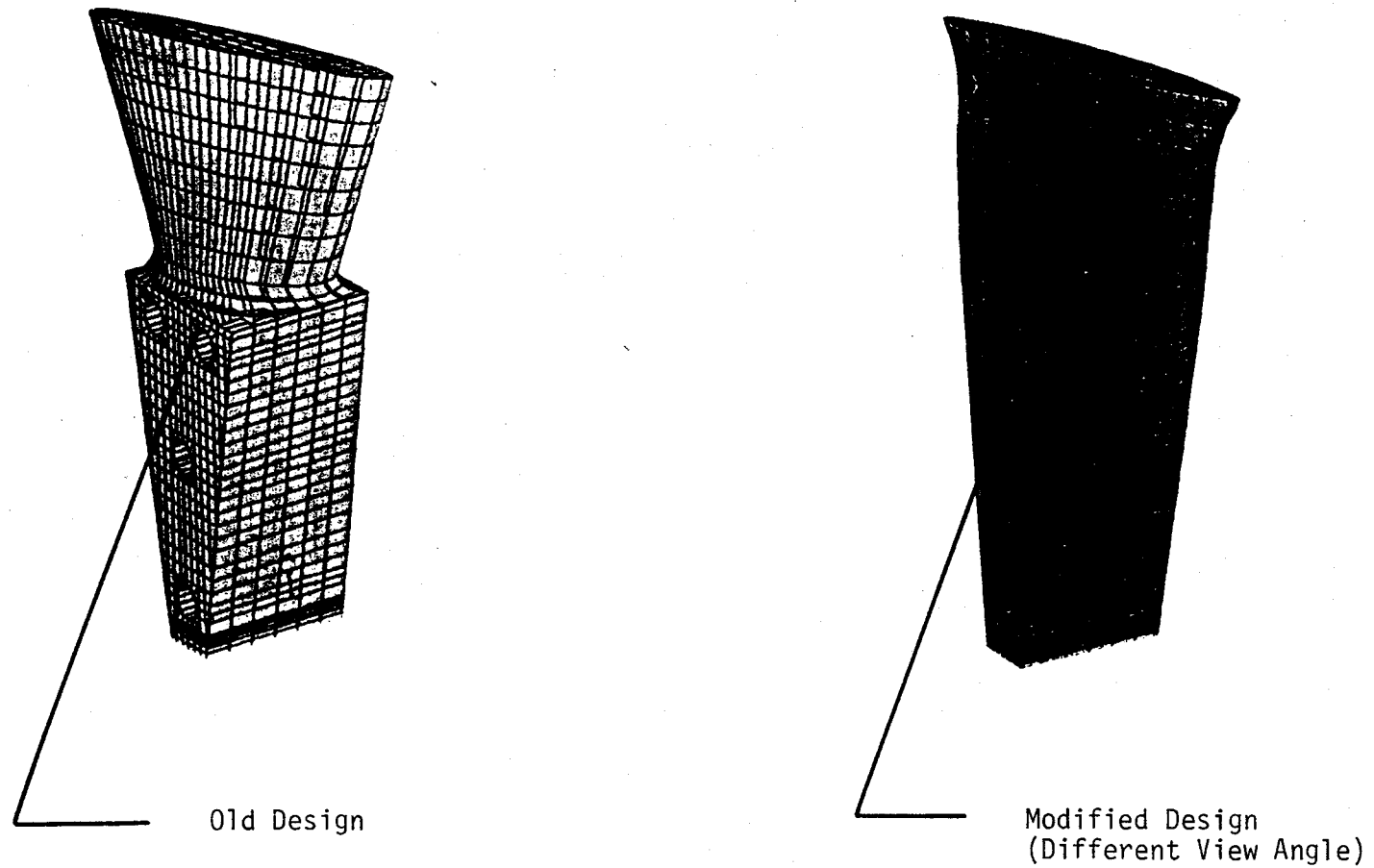


Figure 13. - Finite Element Models of the transition/butt regions for the NASA Langley Research Center 7- by 10-Foot wind tunnel fan blade.

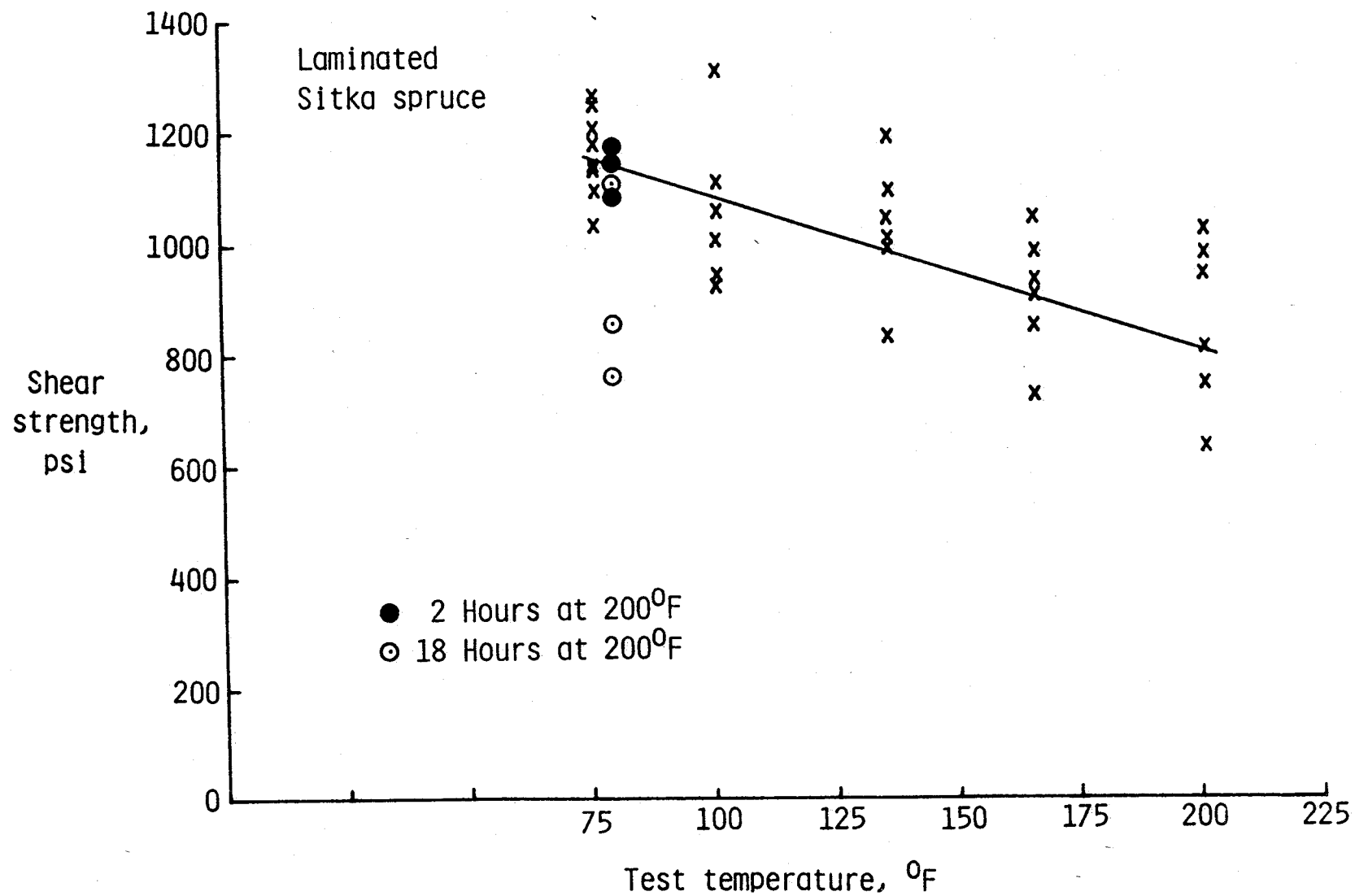


Figure 14.- Shear Strength of Laminated Sitka Spruce as a Function of Temperature.

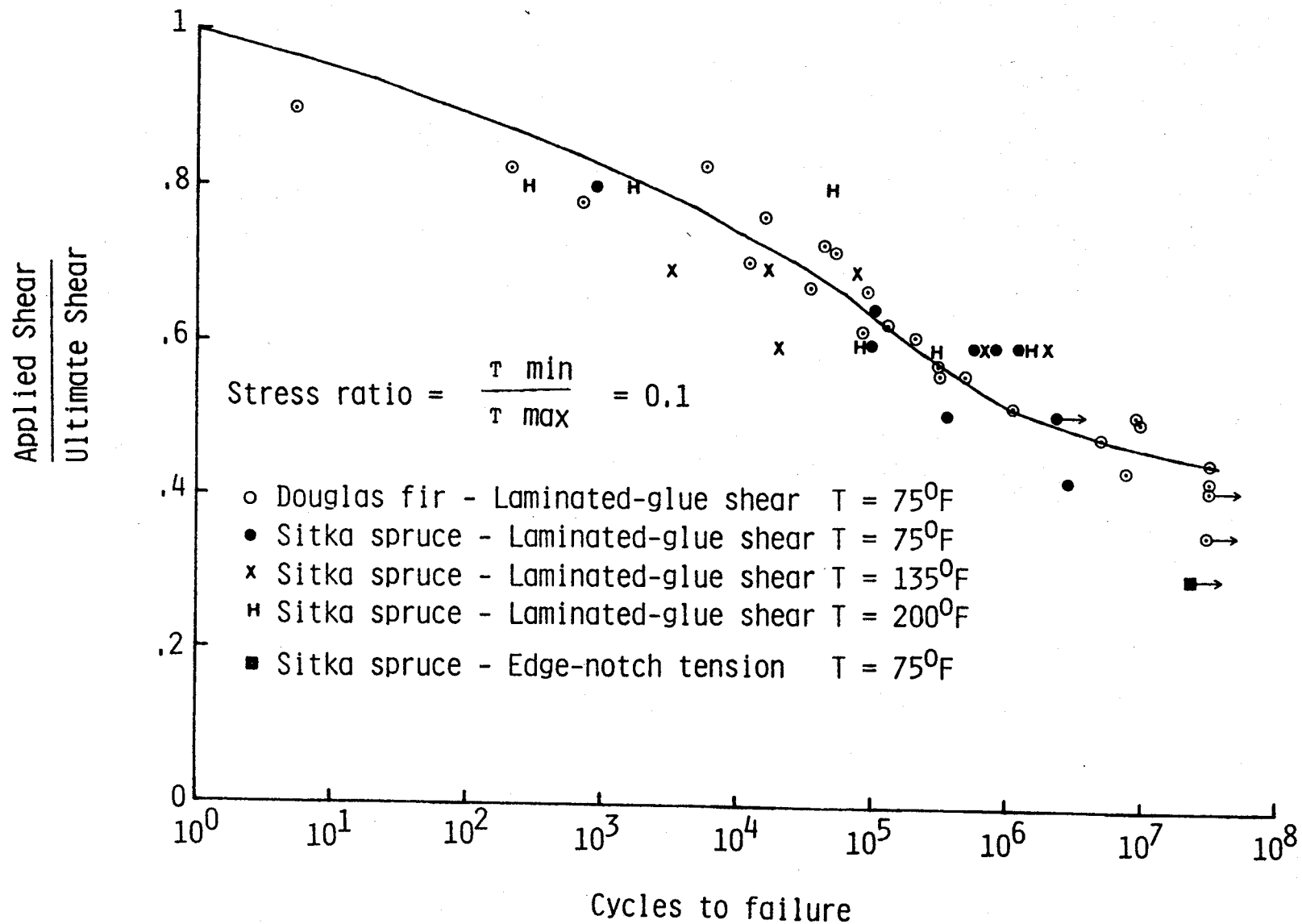
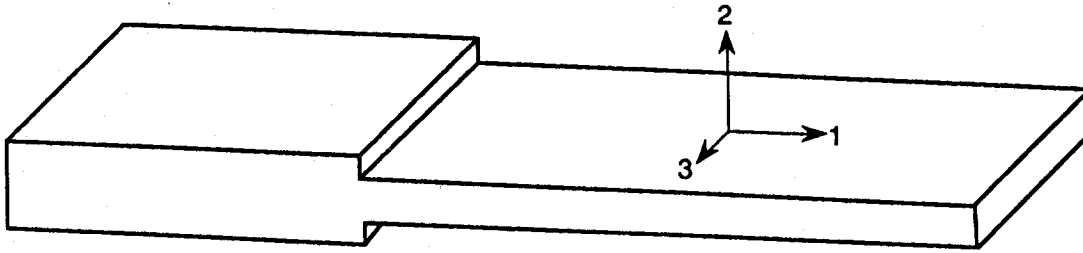


Figure 15. - Fatigue Strength of Laminated Sitka Spruce and Douglas Fir



<u>Constants</u>	<u>Units</u>	<u>Sitka Spruce</u>	<u>Hydulignum</u> <u>25% Cross Ply</u>
<u>Modulus</u>			
$E_1$	psi	1,772,000	2,350,000
$E_2$	psi	87,000	330,000
$E_3$	psi	154,000	780,000
<u>Shear Modulus</u>			
$G_{12}$	psi	117,000	400,000
$G_{13}$	psi	120,000	400,000
$G_{22}$	psi	7,100	150,000
<u>Poisson's Ratio</u>			
$\mu_{12}$		.441	.15
$\mu_{13}$		.375	.25
$\mu_{32}$		.471	.33
$\mu_{23}$		.248	.14
$\mu_{31}$		.034	.08
$\mu_{21}$		.022	.021

Figure 16. - Elastic Material Constants Used in Orthotropic Analyses,  
Room Temperature - 8% Moisture Content

# GOODMAN DIAGRAM — LAMINATED SPRUCE

FATIGUE DATA: R=0.1 MEAN CURVE

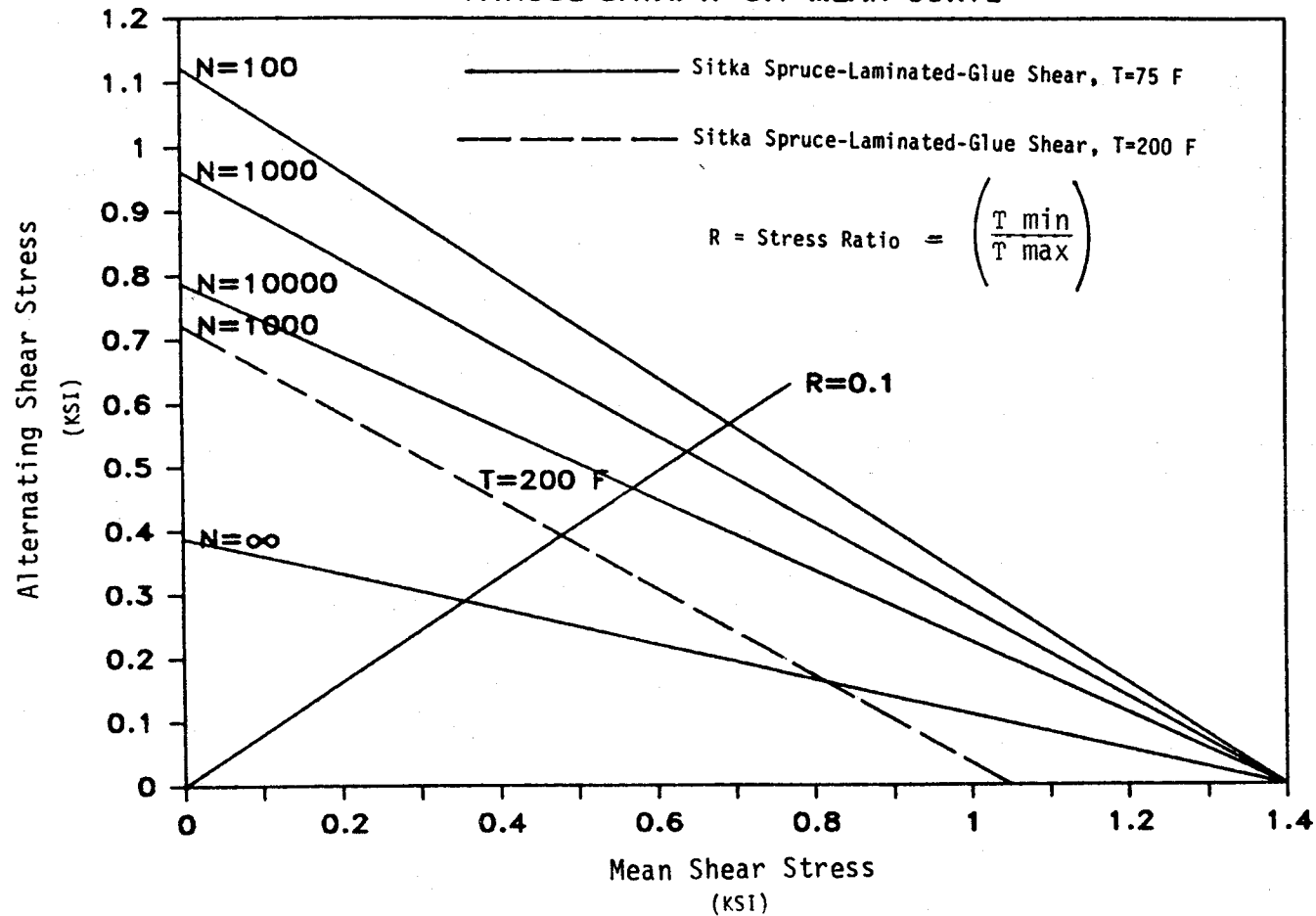


Figure 17. - Goodman Diagram for Laminated Sitka Spruce, Loaded in Shear

7 X 10 FAN BLADE  
CHARACTERIZATION OF CYCLIC LOADING

$$R = \frac{\tau_{\min}}{\tau_{\max}} \approx 0.8 \quad \tau_{\text{mean}} = \frac{\tau_{\max} + \tau_{\min}}{2} \approx 1010 \text{ psi} \quad \tau_{\text{alt}} \approx 140 \text{ psi}$$

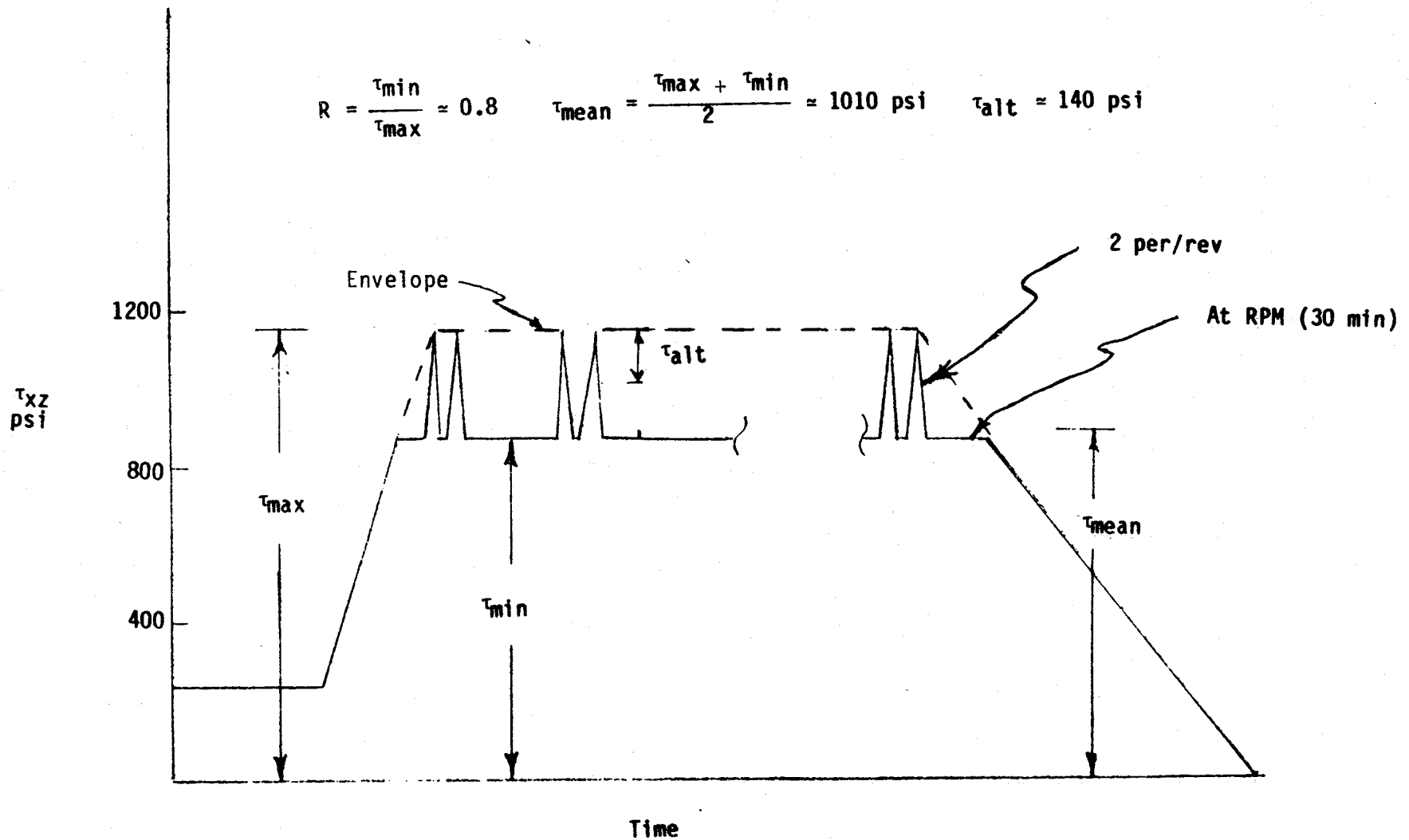


Figure 18. - Cyclic Shear Stress in Region of Highest Loaded Fan Blade Attachment Hole for the NASA Langley Research Center 7- by 10-Foot High Speed Wind Tunnel during Operation at 475 RPM.

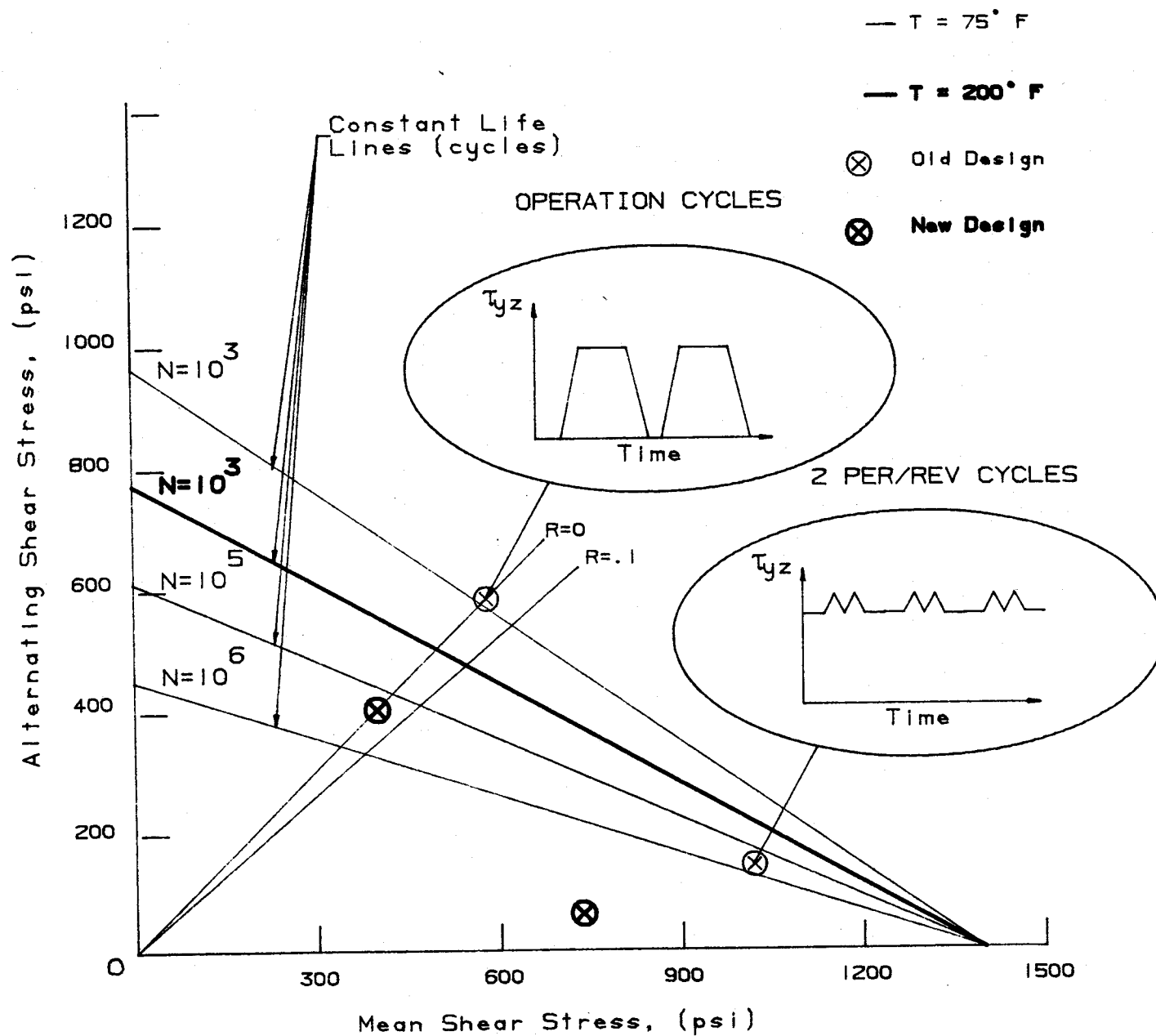


Figure 19. - Goodman Diagram for the 7- by 10-Foot Wind Tunnel Laminated Spruce Blades Illustrating Fatigue Life Predictions for Old and New Design.

NOTE: Samples Held at 90% Relative Humidity for 91 Days Prior to Test

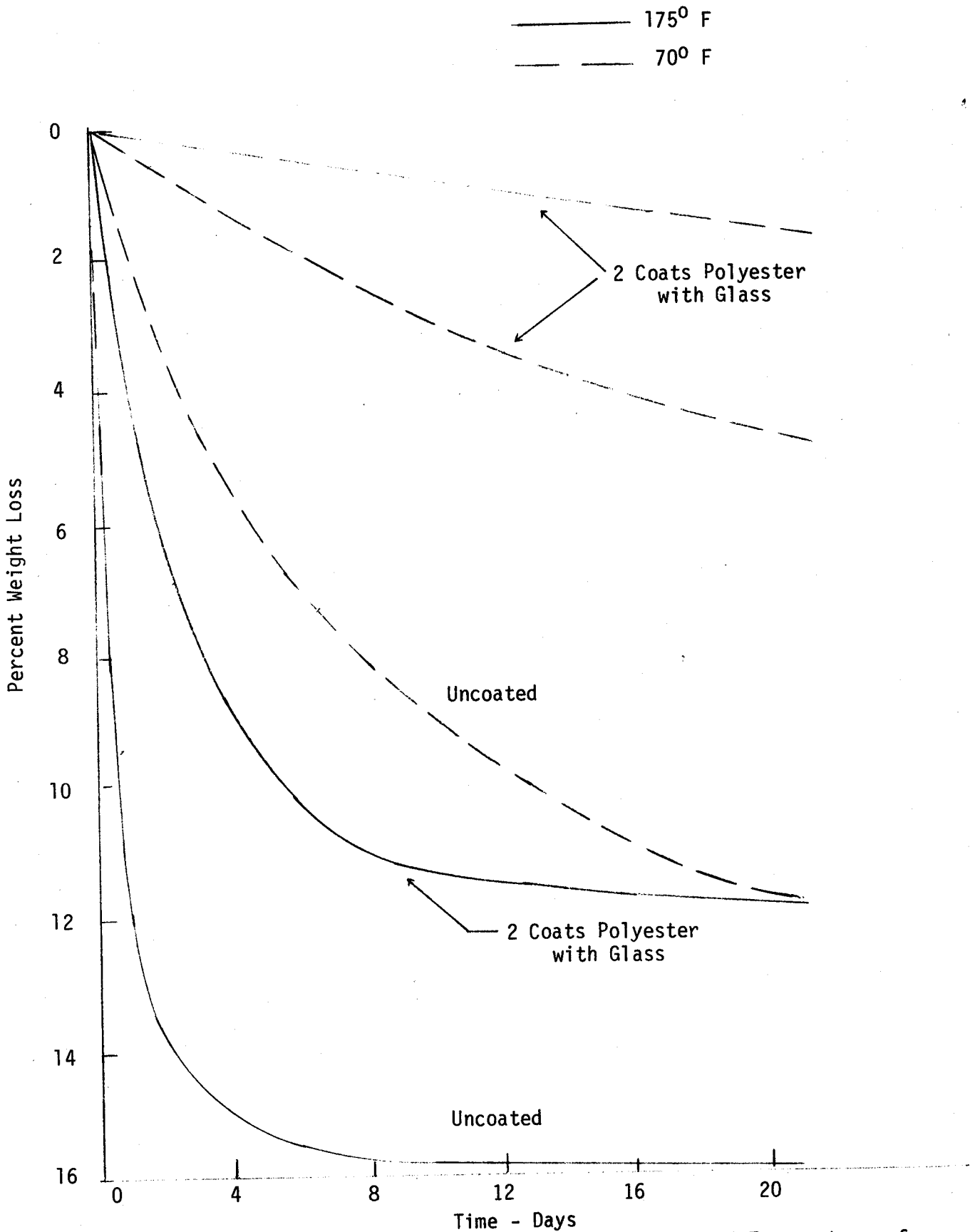


Figure 20. - Coating Effectiveness at Room and Elevated Temperatures for Sitka Spruce Dried Over  $H_2SO_4$  ( 0% Relative Humidity)



# MOISTURE EXCLUSION EFFICIENCY vs TIME

BEST SAMPLE PERFORMANCE OF EACH COATING

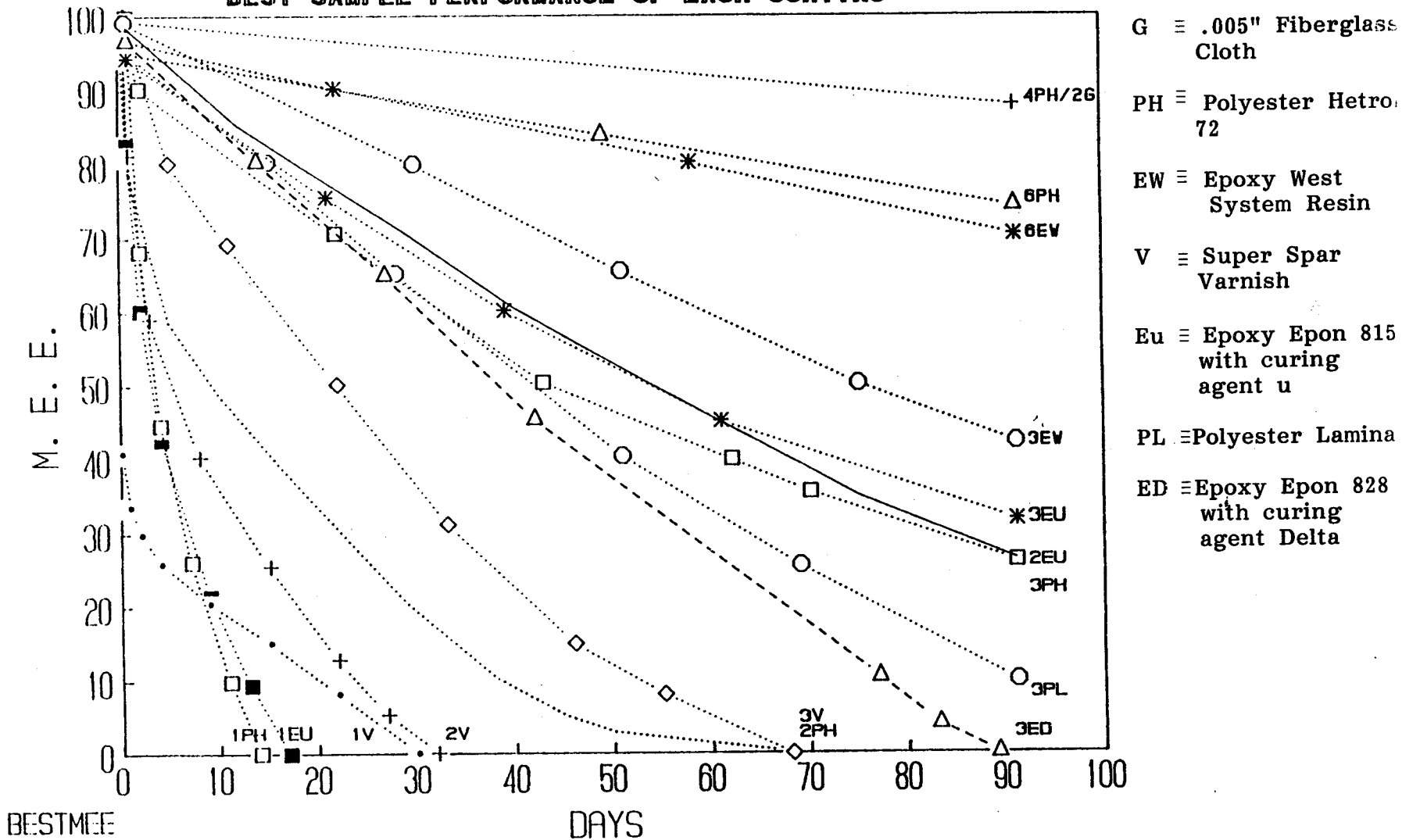


FIGURE 20.- Continued.

Pin reaction load distribution

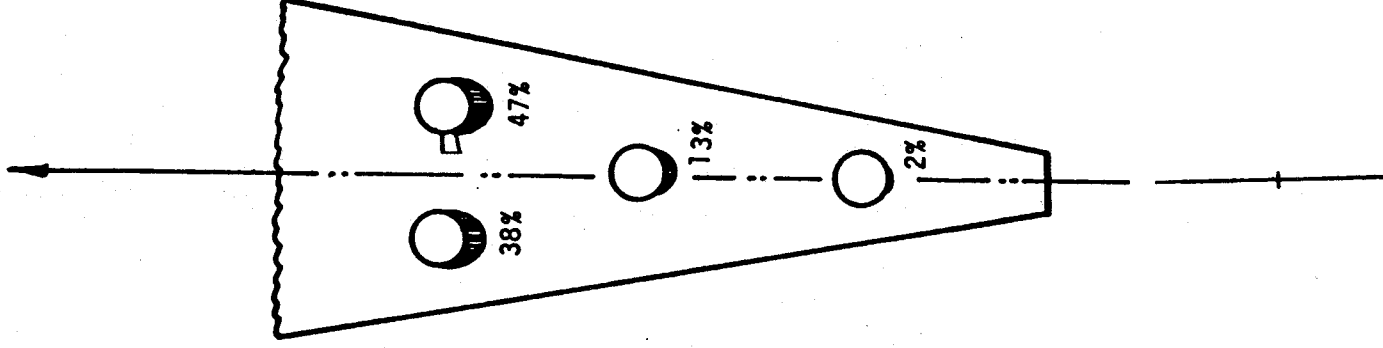


Figure 21. - Attachment pin loads (% of total load) for the NASA Langley Research Center 7-blade 10-Foot High Speed Wind Tunnel fan blades that failed.

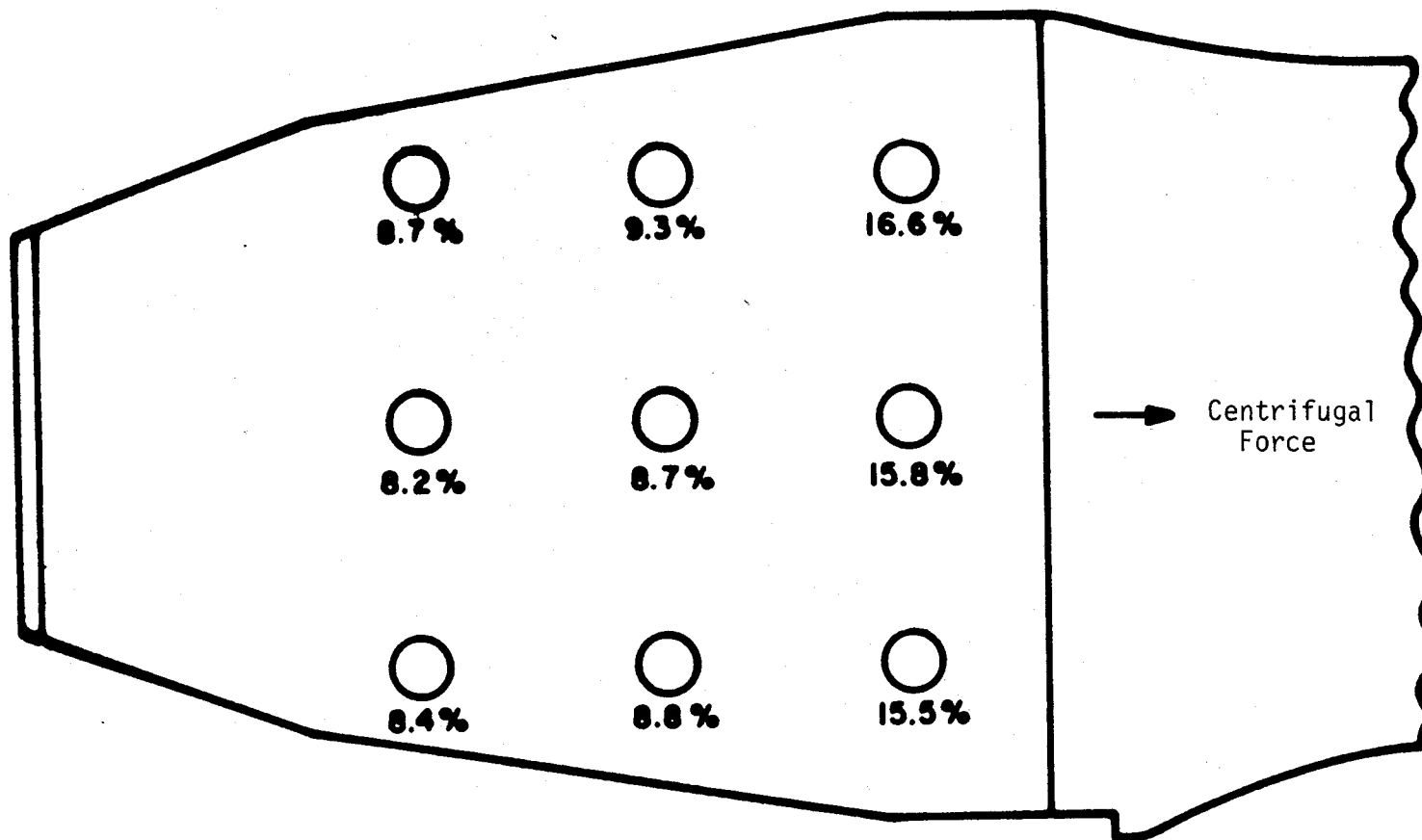


Figure 22. - Attachment bolt loads (% of total load) for the NASA Langley Research Center 16-Foot Wind Tunnel fan blades.

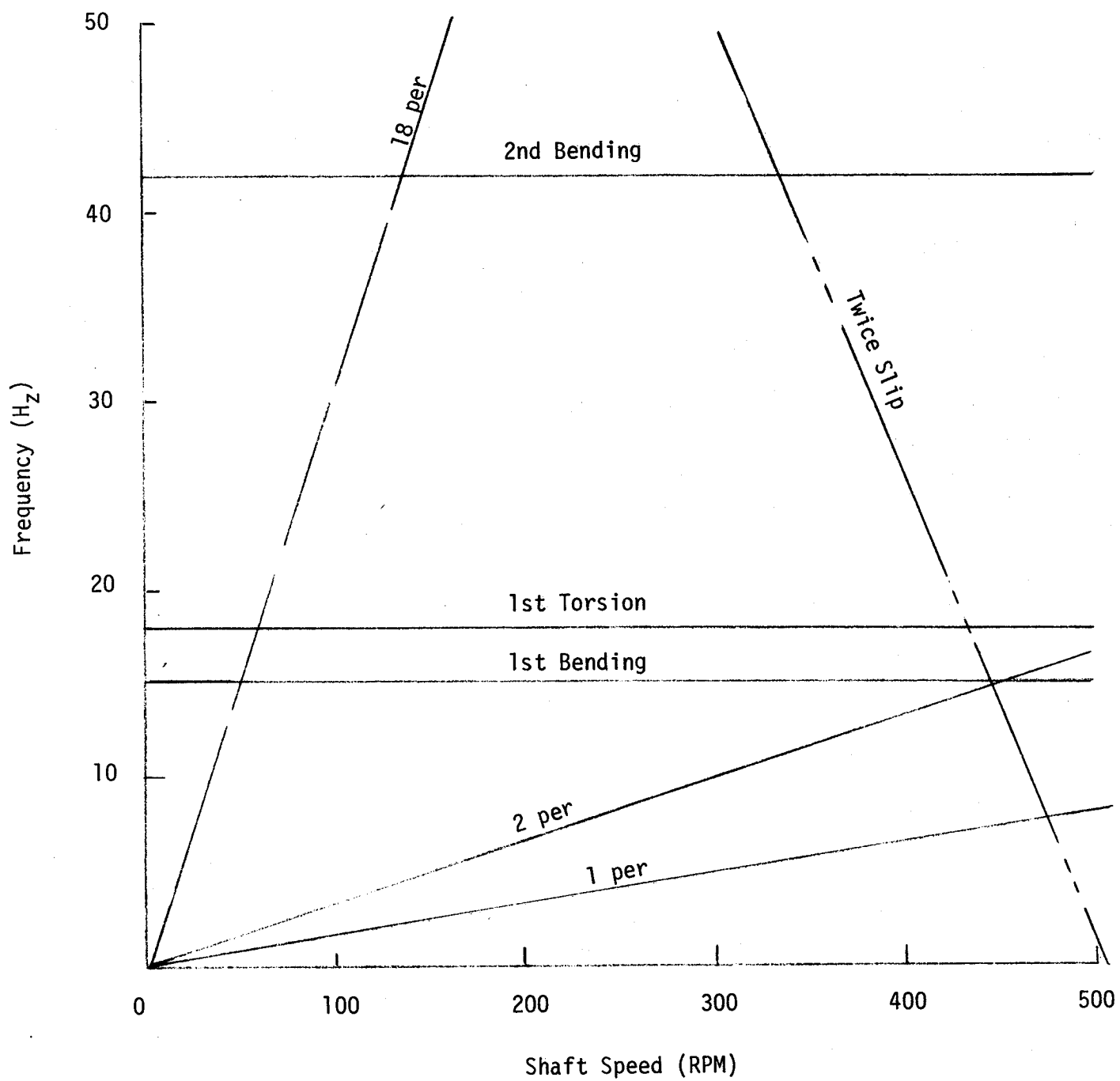


Figure 23. - Interference (Campbell) Diagram for NASA Langley Research Center High Speed 7- by 10-Foot High Speed Wind Tunnel.



## Report Documentation Page

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16. Abstract This report presents information compiled by the NASA Inter-Center Committee on Structural Integrity of Wooden Fan Blades and is intended for use as a guide in design, fabrication, evaluation, and assurance of fan systems using wooden blades. A risk assessment approach for existing NASA wind tunnels with wooden fan blades is provided. Also, state-of-the-art information is provided for wooden fan blade design, drive system considerations, inspection and monitoring methods, and fan blade repair. Proposed research and development activities are discussed, and recommendations are provided which are aimed at future wooden fan blade design activities and safely maintaining existing NASA wind-tunnel fan blades. This report contains information that will be of value to wooden fan blade designers, fabricators, inspectors, and wind-tunnel operations personnel.					
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